Managing weta damage to vines through an understanding of their food, habitat preferences, and the policy environment

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Insects cause major crop losses in New Zealand horticulture production, through either direct plant damage or by vectoring disease Pugh (2013). As a result, they are one of the greatest risks to NZ producing high quality horticulture crops (Gurnsey et al. 2005).

The main method employed to reduce pest damage in NZ horticulture crops is the application of synthetic pesticides (Gurnsey et al. 2005). However, there are a number of negative consequences associated with pesticide use, including non–target animal death (Casida & Quistad 1998) and customer dissatisfaction. Therefore, research is essential to find ecological control methods to manage insect damage in NZ primary industries.

On NZ wineries, insect herbivory is mostly conducted by invasive and common insects. However, in the Awatere Valley, herbivory on newly-formed vine buds is caused by the endemic and iconic weta species *H. promontorius* (Joanne Brady, personal communication, March 5th, 2014). Due to weta having iconic status in New Zealand, there is an extra incentive to find more ecological measures to reduce their effect on wine production.

The objective of my thesis was to assess both ecological control methods and policy strategies to mitigate *H. promontorius* damage on vines, and to conserve the endemic insect. This approach was developed because of the iconic status of weta and because of the increasing knowledge of the negative effects of pesticide use.

Under controlled laboratory conditions, I investigated laboratory maintenance effects of diet, container size, and habitat on the relative growth rate (RGR) and survival of *H. promontorius*. Weta fed a higher protein diet had a significantly higher RGR after 56 days than weta fed a low protein diet. Although death rate between treatments was not significant, there was a tendency for higher protein diets to have a lower death rate than weta fed low protein diets. Container size significantly impacted weta percentage survival when comparing 400 ml to two litre containers; however, there was no significance between two and one litre containers. Habitat factors proved to be non-significant. Further research should investigate all three factors over longer time frames to confirm treatment implications on weta performance.

To test for potential trap crop plants, choice tests were conducted in a controlled temperature room. Both amount of food eaten, and whether food was eaten or not, were much higher for broad bean (*Vicia faba* Linneaus), in the Leaf Trial compared to phacelia (*Phacelia distans* Benths), buckwheat (*Fagopyrum esculentum* Moench), and alyssum (*Lobularia maritime* Linnaeus). In addition, broad bean was the only non-vine plant to be eaten significantly more than a vine plant in a bioassay. Furthermore, the amount of broad bean eaten when paired with a vine bud was significantly more than other non-vine treatments paired with a vine bud. The next step to justify broad bean as a trap crop would be to run trap crop trials on vineyards.

To investigate the distribution of *H. promontorius* on vineyards, transects were constructed on different vineyards. Location of burrows and soil penetration resistance were significantly correlated with *H. promontorius* density. Testing with the same methods needs to be run over consecutive years to compare conditions and to be confident in the results.

Evaluating potential policies to conserve *H. promontorius* on vineyards entailed literature reviews, and interviewing vineyard managers, including some who had previously dealt with controlling other iconic NZ pest species. Results concluded that conservation within businesses relies heavily on government input and businesses having conservation embedded into the company's culture. The next stage would be to trial suggested policies in an applied setting.

Keywords: Weta, *H.promontorius*, trap crop, pest, vineyard, herbivory, pest-resource, iconic, endemic, ecosystem services, agroecology, ecological engineering, integrated pest management

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Chapter 1

Introduction

1.1 Insect Pests

Arthropod pests have hindered crop production since agriculture began 10,000 years ago (Oerke 2006). Consequently, many different control methods have been trialled in an attempt to limit arthropod damage, including pesticides, trap cropping, and biocontrol (Barrett 1991; Oerke 2006). Crop plants are damaged by two groups of arthropods: assimilate sappers and tissue consumers. Assimilate sappers use specialised sucking mouthparts to draw out plant nutrients and carbohydrates. As a secondary effect of the sucking and digesting process, assimilate sappers may inject toxic saliva which damages plant leaves. They can also act as a vector for plant viruses (Oerke 2006; Carner et al. 2012). Additionally, honeydew secreted by some assimilate sappers (such as aphids) can create a fungal coating on leaves which inhibits photosynthesis (Carner et al. 2012). Tissue consumers, on the other hand, use specialised mandibles to feed on plant epidermis when the insects are in an early instar or nymph stage; as they develop, some tissue consumers will eat entire leaves, roots and plant reproductive parts (Oerke 2006; Carner et al. 2012).

Insect crop pests are located in most climates, but favour areas which offer tropical or temperate weather patterns (Oerke 2006). The major pest groups are beetles (Coleoptera), true bugs (Hemiptera), moths and butterflies (Lepidoptera), true flies (Diptera), and crickets, grasshoppers and locusts (Orthoptera) (Singh & Emden 1979; Oerke & Dehne 2004).

The predation of crops by insects inflicts significant economic losses to farmers and governments. For example, the mealy bug (*Phenacoccus manihoti* Matile-Ferrero) is estimated to cause 2 billion US dollars' worth of damage on cassava plants in Africa (Carner et al. 2012) and the melon fly (*Bactrocera cucurbitae* Coquillett) causes 4.5 billion US dollars' worth of damage on pip fruit and tomatoes in California (Californian Department of Food and Agriculture 2014).

Within New Zealand's (NZ) temperate climate, we share many common insect pests with North America and Europe (Steve Wratten, personal communication, Jan 27, 2014). Two major pests include aphids in the family Aphididae in NZ's cereal crops, and the Argentine stem weevil (*Listronous bonariensis* Kuschel,) in NZ's pasture industry (Barker et al. 1986). In NZ's horticulture crops, however, leafroller moths (tissue consumers) in the family Tortricidae cause the greatest impact. Leafrollers do the most damage in pip fruit orchards, but significant damage is also created in NZ's vineyards (Jonathan 2003). There are six species of leaf roller which attack grape vines in NZ. Five are endemic, but the most damage is caused by the light brown apple moth (*Epiphyas postvittana* Walker) which is native to Australia. Although serious damage is created by feeding on new shoots and reproductive parts of a vine (Lo & Murrell 2000), the most significant damage by *E. postvittana* is caused by providing infection sites for *Botrytis* fungus (Scarlett 2005). In favourable conditions for the moth, 20 percent of a vineyard may become infected by the *Botrytis* fungus. In extremely damp seasons, entire losses of vines may occur. In addition, mealybugs have been known to cause significant damage to vineyards in New Zealand (Chapman et al. 1999). Mealybugs are sap sucking insects which contribute to the decrease in vine productiveness through transmitting grapevine leafroller viruses (Jordan 1993). Moreover, their excretion of honeydew causes fungi to develop on vine leaves (Buchanan et al. 2003). In recent years, the endemic NZ grass grub beetle (*Costelytra zealandica* White) and the endemic weta *Hemiandrus promontorius* (Orthoptera: Anostostomatidae) have become pests in some wine growing areas. *Costelytra zealandica* has been an established pest in NZ's pasture for decades (Grimont et al. 1988), and the recent infiltration into wineries is causing significant economic costs to winegrowers. *Costelytra Zealandia* defoliates leaves and damages shoots and inflorescences in late spring (Wine 2014). *Hemiandrus promontorius* has only recently become a pest on vineyards in the Awatere Valley. This species of weta thrives in the under-row irrigated areas and, during springtime, feeds on the newly developed *Vitis vinifera* (Linneaus) leaves and buds (Brady 2014). Controlling for insect pests is therefore necessary in NZ's horticulture industry to insure high quality crops are produced.

1.2 Pesticides

Pesticide use is the main method of dealing with arthropod damage in worldwide agriculture. Pesticide use dates back to 2500BC, where the Sumerian peoples rubbed sulphur compounds onto their bodies to deter insects. However, the earliest recorded use of insecticides in a field environment was by the Chinese in 800AD, where they used a combination of arsenic and water to control insects on citrus orchards. In the 1800s, pyrethrum, a natural insecticide made from *Chrysanthemum* plant blossoms, was in use and by the 1900s lead – arsenate was being sprayed over crops (Holley et al. 2007). By the 1950s, farmers were beginning to apply synthetic pesticides to target the nervous systems of pests. The first major synthetic insecticides were chlorinated hydrocarbons (OCs) such as dichlorodiphenyltrichloroethane (DDT). Chlorinated hydrocarbons disrupt the transfer of nerve impulses by inhibiting potassium and ATPase, which controls the active transfer of ions through membranes. Although DDT was successful in controlling some insects, its lack of solubility in water caused it to bio-accumulate in environments, becoming toxic to animals and non-target invertebrates (Casida & Quistad 1998). As a result, synthetic organophosphate compounds (OPs) which are more biodegradable than OCs, became popular as an insecticide application during the 1970s. OPs cause acetylcholine to build up in insects, resulting in excessive nerve stimulation (Michigan Department of Natural Resources 2014). Organophosphate compounds, though, have been linked to a number of harmful effects in terrestrial animals, aquatic wildlife, and humans. Residues of OPs, for example, have been found to be toxic to mammals and birds (United States Environmental Protection Agency 2013a) and they have been linked with memory loss in bee populations. The Environmental Protection Authority (EPA) of the USA began phasing out OPs in the year 2000 when they were detected in ground water systems and linked to human health risks (Fairbrothe et al. 2014). From the 1970s, pyrethroids, synthetic compounds based on pyrethrum, were being used extensively as an insecticide. Pyrethroids were heralded due to greater site specificity, and their toxicity can be altered to suit the working environment (Bajomi et al. 1996). Like OPs, pyrethroids cause over-stimulation of nerve cells (Casida & Quistad 1998); however, they have been proven to be less harmful to humans and terrestrial wildlife than OPs, despite extreme toxicity to fish and invertebrates (Fishel 2005).

Although banned in some countries, OPs are still used in NZ. However, according to Barley et al. (2009), there has been a significant reduction in the use of OPs in NZ's pip fruit industry. In NZ wineries, pythrethroids are the main compounds used to control arthropods (Steve Wratten, personal communication Feb 8th, 2014). However, OPs such as Chlorpyrifos and Diazinon are still in use (Barley et al. 2009).

Recent introductions into the insecticide industry include neonicotinoids and insect growth regulators (IGRs) (Oerke 2006). Neonicotinoids target neural activity, and are the most widely-used insecticides in the world. In 2006, 1.7 billion US dollars of neonicotinoids were sold. Neonicotinoids are a popular choice of insecticide because they are less toxic to mammals than other compounds and they are effective at targeting the biochemical target site of insects (Oerke 2006). However, recent studies have suggested that neonicotinoids could be the cause of honey bee population collapses (Girolami et al. 2009). IGRs mimic hormones which affect physiological processes critical to insect development. Therefore, IGRs are not necessarily toxic to the target species, but instead rely on creating a physiological abnormality (Siddall 1976). According to Delaplane (1996), IGRs have been used increasingly over the last 20 years because they have minimal effects on non-target species.

1.3 NZ wine industry

Between the years 1990 and 2000, the total vineyard area in NZ doubled (Berndt 2002) and in the last 10 years, wine exports have increased 500 percent (Berndt 2002). The wine industry is now NZ's eighth largest export earner, with annual earnings of 1.2 billion NZD (Deloitte 2014). The export value of NZ wines has increased by 22% since 2009, mainly due to export sales in Australia, North America, and China (New Zealand Wine 2013a). The wine produced in NZ is of a premium standard (The Wine Economist 2008; New Zealand Trade & Enterprise 2014). These standards were showcased at the 2012 Decanter World Wine Awards, where 92% of NZ's entered wines won a medal (New Zealand Trade & Enterprise 2014). Although NZ produces a number of different grape varieties, Sauvignon Blanc (*Vitis vinifera L*. Cv.) dominates NZ vineyards, making up 68% of production and 83% of NZ wine exported. Marlborough is the largest producer of Sauvignon Blanc in New Zealand with 17829 hectares, followed by Hawkes Bay with 1004 hectares (New Zealand Wine 2014d).

1.4 Sustainable Practice

While the NZ wine industry generates high GDP, NZ only contributes 0.2% of world wine production, indicating significant potential for growth (Deloitte 2014). To help increase exports, the 'New Zealand Wine' set up a management programme called Sustainable Wine Growing New Zealand (SWNZ). The aim of SWNZ is to encourage sustainable practice on vineyards, and in doing so strengthen the case that NZ's clean and green branding applies to the wine industry. Among other things, SWNZ promotes increasing plant diversity, reducing pesticide application, improving soil health, and sensible irrigation plans (New Zealand Wine 2014c). By adopting management techniques that promote these aspects, ecosystem services on wineries may increase, and therefore benefit biodiversity and vine health. Ecosystem services provided by deploying non-crop plants include soil retention, weed suppression, and biological control. For example, a study by Jonsson et al. (2010) showed that planting buckwheat (*Fagopyrum esculentum* Moench), alyssum (*Lobularia maritime* Linnaeus), and phacelia (*Phacelia distans* Benths) helped to control light-brown apple moth by attracting parasitic wasps.

1.5 Constellation Brands support

Constellation Brands, the owner of many of New Zealand's leading wine brands, is experiencing damage to their vines in the Awatere Valley from *H. promontorius* predation. As a result, they have allowed me access to some of their vineyards in order to study weta ecology and damage and to contribute to future sustainable solutions.

1.6 Study species '*Hemiandrus promontorius*'

Hemiandrus promontorius is the current scientific name for my study organism. However no paper has been written classifying this species and therefore this name is not accepted by international biosystematics. This species is part of the 'ground' weta group which consists of all weta in the *Hemiandrus* genus (Bowie 2012). However tree weta consisting of all weta in the *Hemideina* genus are also often referred to as 'ground dwelling' weta (Johns 2001). Until recently, *Hemiandrus promontorius* was only thought to live in close proximity to coastal areas in the Marlborough region and therefore was considered a 'restricted species' (Johns 2001) which, under the Department of Conservation ratings, means this species could be classified as 'at risk' (Department of Conservation 2014g). The range of this species is now known to overlap with agricultural areas, where they have become a serious pest in Marlborough vineyards (Joanne Brady, personal communication, March 5th, 2014). In 2011 and 2012, wine production was completely lost from one 200 ha winery block due to *H. promontorius* predation; the damage caused economic losses estimated at 2.4 million NZD (New Zealand Wine 2013b). *Hemiandrus promontorius* feeds on leaves and vine buds (Fig. 1) which usually emerge in the first two weeks of October (Jackson 2008). Damage, according to Joanne Brady, (personal communication, March 5th, 2014) lasts until the shoots have three leaves (roughly between one and two weeks). Vines can respond by sending out a new shoot; however, this shoot is delayed in its development in relation to older undamaged shoots in the vicinity, and subsequently its crop will be behind the other grapes at harvest time (Jackson, 2008). *Hemiandrus promontorius* damages many different vine varieties, but the heaviest and most costly damage occurs on *Vitis vinifera L*. Cv. Sauvignon Blanc. Sauvignon Blanc is the most economically significant vine variety in Blenheim's export market (New Zealand Wine 2014d).

Figure 1. *Hemiandrus promontorius* feeding on a vine leaf (Brady 2013).

1.6.1 *H.promontorius* taxonomy

Kingdom: Animalia

Phylum: Arthropoda

Class: Insecta

Order: Orthoptera

Sub order: Ensifera

Family: Anostostomatidae

Sub family: Anostostomatinae

Genus: *Hemiandrus*

Species: *promontorius*

1.6.2 Morphology

Little is known about *H. promontorius*; to date, no papers have been published on this species. Nevertheless, there is published information regarding the behaviour and morphology of species within the *Hemiandrus* genus. Species in the *Hemiandrus* genus are usually between 15 mm and 30 mm in body length, with the majority not growing beyond 22 mm. They are not sexually dimorphic. All known species of ground weta have abdominal femoral stimulatory mechanisms consisting of sparse rows of sharp pegs located on the femur, and small areas of miniscule spines on at least three of the abdominal tergites (Field 1993).

1.6.3 Communication

Ground weta use both vibratory and chemical signals to communicate. Abdominal drumming and substrate vibration is used when attempting to attract a mate (Gwynne 2004). Pheromone-based communication consists of odorous anal secretions deposited by ground weta at mating time (Gwynne 2004).

1.6.4 Burrowing behaviour

Hemiandrus spp. favour different substrate types for burrowing sites, including loess and fine volcanic soils, dense moss, and sandy-clay soils. Anecdotal evidence suggests *H. promontorius* may prefer sandy loams as a burrow substrate, as soils in the Marlborough area where damage is occurring are mostly sandy loams (Johns 2001). Observations by vineyard staff suggest that burrows are more common in the under-vine zone. *H. promontorius* burrows to a depth of around 25 cm in spring, and burrows slightly deeper in winter months when protecting eggs (Peter Johns, personal communication, March 8th, 2014).

1.6.5 Nest guarding

Nest guarding is uncommon for ground weta, but is exhibited by some *Hemiandrus* spp. (Wahid 1978; Cary 1983; Gwynne 2004). For instance, *H. pallitarsis* , *H. vicinius* and *H. promontorius* were found by Gwynne (2004) to not exit burrow holes for several months after constructing their brood chamber.

1.6.6 Progressive life stage development and behaviour

Weta in the *Hemiandrus* genus have a life-cycle of two years. When they first hatch, their cuticle is pale blue, but it deepens to a purple tinge with each moult. Once their cuticle has hardened, weta usually consume some of the waste exuviae (Stringer & Cary 2001). According to Richards (1954), cannibalism occurs in some weta species during ecdysis.

1.6.7 Habitat

H. promontorius were originally only thought to be located on Marfell's beach, Cape Campbell (Johns 2001). It is now commonly found in the Awatere Valley. Trapping of *H. promontorius* has concluded that this ground weta can be found in habitats consisting of low scrubby undergrowth plant species including native flax (*Phormium* sp.), Ngaio (*Myoporium laetum*), *Cassinia* sp., and exotic grasses (Johns 2001).

1.6.8 Diet

Although the diet of *H. promontorius* has not been examined, studies have proven other ground weta species to be largely herbivorous*,* as are the majority of New Zealand weta species (Cary 1983; Johns 2001; Winks et al. 2002; Morgan-Richards et al. 2008). However, some species of ground weta will eat other insects. For instance, Cary (1983) reports that *H. maori* will digest insect material and Wyngaarden (1995) states the Tekapo ground weta (*Hemiandrus* n. sp) is an omnivore.

1.7 Integrated Pest management and Ecological Engineering

The use of Integrated Pest Management (IPM) components is not new to the 20th century. In fact, before the production of powerful pesticides, farmers relied on information regarding pest biology and used multi-tactical techniques to manage pests (Gaines 1957). Integrated pest management is defined by Gurr et al. (2004) as 'the combined use of multiple pest-control methods, informed by monitoring of pest densities.' A broader definition was adopted by the Food and Agriculture organization of the United Nations (FAO): 'Integrated Pest Control is a pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest population at levels below those causing economic injury' (Kogan 1998). Within IPM, cultural, biological, chemical and horticultural practices are used to manage pest outbreaks (Sandler 2010). Therefore, although usually not the first option explored, synthetic chemical application, such as spraying trap plants with pheromones or pesticides is readily accepted under IPM. Ecological Engineering, on the other hand, focuses on using naturally occurring abiotic and biotic processes to manipulate farm habitats to make them less favourable for pests and, therefore, synthetic chemical use is a last resource (Altieri et al. 2004; Gurr et al. 2004).

1.7.1 Trap crops

One IPM and EE method is trap cropping. Trap cropping is defined by (Mizell 2012) as the 'presence of a second crop in the surrounding area of a commercial crop to divert a pest which would attack the commercial crop.' Lukhwareni (2013) explains that the trap crop may be sacrificial or it may be harvestable. According to Shelton and Badenes-Perez (2006), the modalities of trap crops are defined by plant characteristics and how the plants are deployed in time or space. Besides conventional trap cropping, trap crops may be classified as dean end, push pull, perimeter, multiple and sequential. It is often the case that multiple classifications exist within a particular trap crop (Shelton & Badenes-Perez 2006). Under an IPM system trap crops may be sprayed with synthetic chemicals to assist in controlling insect pests, whereas under an EE system farmers are more likely to rely on plant diversity and a plant's natural chemicals to control insect herbivory (Altieri et al. 2004).

1.7.2 Biological control

Biological control (BC) is another form of IPM and EE. Biological control is defined as 'the use of *natural enemies*—predators, parasites, pathogens, and competitors—to control pests and their damage.' This includes humans physically releasing natural enemies. A sub form of BC is conservation biological control (CBC). Gurr et al. (2007) reports that CBC seeks to improve the use of existing species rather than introducing exotic insects and therefore is more of an EE approach. The planting of one species can provide multiple ecosystem benefits. An example includes lucerne strips attracting the green crop mirid pest away from cotton plants in Australia and attracting natural parasites of cash crop eating insects. Another example is the broad bean (*Vicia faba* Linneaus) plant, which is not only attractive to the leaf miner pest (Kogan 1998) but also attracts beneficial hymenoptera insects (Aouar-Sadli et al. 2008). However, the employment of CBC strategies is slow (Falconer & Hodge 2000; Pietola & Lansink 2001). Griffiths et al. (2008) suggest that the slow uptake of CBC tactics is related to risk perceptions and the difficulty to achieve a price premium in markets (Griffiths et al. 2008). Furthermore, Hoddle (2004) suggests that the adoption of biological control is directly related to a decrease in pesticide and labour costs.

1.8 Climate of Study site

The Marlborough region is located towards the north of the South Island in NZ, running from the Pacific Ocean coastline on the east coast and stretching towards the Kaikoura Ranges in the west. The latitudinal location of Marlborough is 41.3° south, which is within the range (28-50°) where many wine-growing regions are found around the world. Marlborough is one of NZ's driest and sunniest regions, due to high country hills in the west and south, sheltering the region (Wine Marlborough 2014b). The annual mean sunshine hours in Marlborough are around 2,400 per year (New Zealand Wine 2014a) compared to the mean of 2079 for New Zealand's cities (Immagine New Zealand Immigration 2014). Although Marlborough experiences high sunshine hours, the region's close proximity to the Pacific Ocean means that easterly breezes create cool temperatures (Wine Marlborough 2014b); the easterlies are a major reason for the marked diurnal temperature variations which can create 10°C changes between the sunny days and cold nights of autumn (Wine Marlborough 2014a). Typical maximum air temperatures during summer in Marlborough range from 20-26°C, and the mean annual rainfall in Marlborough between 1981 and 2010 was 711 mm (NIWA 2013).

1.9 Geography of study site

Most of the soils in the Marlborough region were laid down during the Pleistocene Epoch. The process began 14,000 years ago whereby glaciers began eroding high country hill faces and snow melt carried the sediments and minerals down towards the Pacific Coast. As a result, most of the vineyards are grown on top of river terraces which provide low to medium fertility alluvial soil (Wine Marlborough 2014b). Soil compositions vary throughout the region in relation to their proximity to riverbeds and exposure to wind (New Zealand Wine 2014a), but consistently sit on top of free draining shingle (Wine Marlborough 2014a).

The Awatere Valley is the southernmost vine-growing sub region in Marlborough, lying south of the Wither Hills between Black Birch Range and the inland Kaikoura Range. The valley runs parallel to the Pacific Coast, and is situated closer to the coast than the Wairau and Southern valleys (Fig. 2). Within this sub region are the Redwood Pass, Sea View, Awatere River, and Blind River areas (New Zealand Wine 2014b). The Awatere Valley is the smallest of the three vine growing regions, with the latest data from the Marlborough District Council stating that the Awatere and Southern Valley collectively have 6822 producing hectares, compared to the Wairau Valley which has over 23,000 vine producing hectares (Marlborough District Council 2014).

The Awatere Valley is characterised by cooler temperatures and drier conditions than the Wairau Valley as it is more exposed to windy weather patterns from the south coast (New Zealand Wine

2014b). The mean annual summer air temperature is around 16 degrees and the mean annual rainfall in the Awatere Valley between 1995 and 2012 was 558 mm (Marlborough Research Centre 2013).

Most of the vineyards in this sub region sit on old terraces from the Awatere River, but some planting does occur on hill side blocks (Wine Searcher 2014). Soil types consist of alluvial stony deposits, loamy topsoil, grey clay and silt sand. The composition of the soil depends on the vine blocks position in relation to rivers and flood plains. Blocks close to the Awatere River tend to have soils with stony deposits. Blocks further away from the river tend to have more of a clay topsoil (The Crossings 2012).

Figure 2. Map showing the position of the Awatere Valley vine growing region in relation to (a) Marlboroughs main vine growing region the Wairau Valley and (b) the Awatere Valleys proximity to the pacific coast and kaikoura ranges (purple boundary = Wairau Valley; red boundary = Awatere Valley; brown boundary = Marfells beach, cape Campbell; blue lines running through the Wairau and Awatere boundaries indicate rivers). Yellow dot on the map in the right hand corner illustrates Marlboroughs position in relation to other districts in New Zealand not depicted in the main map (Source : “Marlborough Region”. 42°29’22.43” S 173°25’17.98” E. Google Earth. January 22nd 2014).

1.10 Aims and objectives

This project is based upon assessing both ecological control methods and policy strategies to mitigate *H. promontorius* damage on vines and to conserve the endemic insect. This approach was developed because of the iconic status of weta and because of the increasing knowledge of the negative effects of pesticide use.

Since little is known about the ecology and biology of *H. promontorius*, exploratory testing needs to take place before control methods and business policies can be tested in an applied setting. Therefore, to give important insight into *H. promontorius* maintenance preferences, feeding preferences, ecology, and the policies proven to be successful in managing an iconic pest, the following objectives were explored experimentally:

1) Investigate methods of maintaining *H. promontorius* health in a controlled captive environment.

2) Compare the feeding preference of *H. promontorius* when given the choice between potential trap crop plants phacelia, alyssum, buckwheat and broad bean; and compare whether trap crop leaves are preferred over grapevine leaves and buds in pairwise choice tests.

3) Take abiotic measurements and weta density levels along transect lines on vineyards to investigate whether certain conditions correlate with weta numbers.

4) Investigate potential policies that may be effective for conserving *H. promontorius* populations on vineyards by interviewing both vineyard managers and individuals experienced at controlling an iconic New Zealand pest.

Chapter 2

Laboratory Maintenance of Weta

2.1 Introduction

Insect rearing is an art which has been practised and refined for thousands of years. Historical records show silkworms were reared for their prized silk material as early as 5000 BC and insects were reared for medicinal purposes over 2000 years ago (Yonghua & Xiwu 1997). At present, insects are also reared for other objectives including conservation (Pearce-Kelly et al. 1998), testing specific behavioural and biological traits (luong - Skovmand 2001), a protein food source for animals (Yonghua & Xiwu 1997), and as a biocontrol agent in agricultural settings (Carson Cohen 2001). No strict definition of rearing exists, but the term usually refers to the reproduction and laboratory maintenance of a target species within controlled environments (Singh 1982; Pearce-Kelly et al. 1998). Laboratory maintenance is a critical element of the rearing process, as most objectives require the production of healthy individuals (Boller 1972; Schneider 2014).

Most insects require a temperature of approximately 26°C and a relative humidity of 55 – 65%. However, specific requirements vary between species (Singh 1982). Finding a species' specific requirements may entail testing field conditions where the target species are known to inhabit, or surveying current literature (Singh 1982). Both humidity and temperature need to be regularly monitored as both impact moisture levels which can lead to drowning (Singh 1982) or influence other rearing conditions (e.g. soil, fungal growth, food quality) (United Nations 2012). McIntyre (2001) mentions the nocturnal activity of giant weta (*Deinacrida*) in their study was related to ambient temperature; another study by Watts et al. (2012) found that *D. rugosa* movements increased with rising temperature. In a third study, Chappell et al. (2014) found that mean soil and air temperature correlated with *Hemiandrus maculifrons* (Walker) being observed outside their burrows, however this behaviour was not correlated with relative humidity. Moreover, Watts et al. (2012) report that three weta died in their experiment when temperature was below 8.4°C, suggesting these mortalities may have been linked to temperature. In a DOC report on caring for weta species, Barrett (1991) suggests the temperature within weta enclosures should range between 15- 20°C. Below 10°C and the weta become inactive; above 25°C, weta become obviously stressed. Humidity levels between 50-80% are optimal, depending on the species (Barrett 1991). In previous experiments, tusked weta hatchlings (*Motuweta isolate* Johns,) have been kept in enclosures at 16-18°C with a 14:8h (light:dark) period in a constant (CT) room (Grant et al. 2006). Wellington tree weta (*Hemideina crassidens* Blanchard) have been successfully cultured in a CT room at 10-20°C (Kelly 2006b) with a 10:14h light:dark period and successfully reared at 15°C with a 14:8h light:dark photo regime (Wehi et al. 2013). To maintain optimal ranges of temperature and humidity for weta, Barrett (1991) and Fisher et al. (2007) recommend misting containers when humidity is low and the soil is dry.

According to Singh (1982), rearing container selection depends on the stage and behaviour of the insect. Suitable containers provide adequate room for movement and ventilation, are non–toxic, and do not allow the insect to escape (Singh 1982). In previous studies, individual tusked weta (Anostostomatidae) have been housed in 2 litre ice-cream containers (Grant et al. 2006), and tree weta (Anostostomatidae) in 2 litre plastic containers for general laboratory maintenance and frass analysis (Wehi et al. 2013). Additionally, 2 litre plastic containers have been used as shelter for weta within larger mating cages (Fowler et al. 2002) and for transferring weta caught on an offshore island to an ecological island sanctuary (Watts et al. 2012). Furthermore, gravid grasshoppers, which are in the same order as weta, have also been reared for experiments in plastic containers (Unsicker et al. 2008).

Weta use their burrows as shelter from predators and harsh weather conditions and also oviposit and rear nymphs in their burrows (Lukhwareni 2013). Choosing conditions to excavate burrows, however, is not universal amongst orthopteran species. Lukhwareni (2013) reports that the most vital environmental characteristic that correlates to the Tekapo ground weta's distribution (*Hemiandrus new* sp., Orthoptera: Anostostomatidae) is fine, silty soil. Burrows may be easier to dig in silty soil and less likely to collapse. Additionally, Wahid (1978) reports that *Hemiandrus* spp. preferred oviposition sites with slightly higher levels of sand and lower proportions of clay. The author suggests that this may be because clay particles stick to the wetas' mandibles, hindering chamber digging. Different substrate soils have been used for weta trials, rearing and maintenance. Fowler et al. (2002) and Grant et al. (2006) used vermiculite as a substrate for subadult and male tree weta. However, Grant et al. (2006) preferred a mixed substrate of pumice, peat and soil for ovipositing female tree weta. Wahid (1978) used a 1:1 substrate mixture of peat and sand for second instar ground weta laboratory maintenance. Furthermore, (Barrett 1991) used soil as a substrate for both maintenance and oviposition. The authors also suggest having a layer of leaf litter on the bottom and top of the soil substrate to replicate natural conditions, absorb moisture, and prevent the compacted soil surface from damaging weta tarsi. Wahid (1978) suggests soil substrates need to be kept moist, otherwise chambers may collapse and the particles may stick to body parts of the weta. Grant et al. (2006) kept vermiculite moist by misting containers with tap water when required and Wehi et al. (2013) systematically sprayed weta containers with water every two days.

Diet is considered one of the most important components of weta husbandry (Morelli et al. 2012). In particular, the presence of nitrogen is critical for entomophagous insects (Joern & Behmer 1997).This is because nitrogen plays an essential role in growth, survival, and reproduction (Bertram et al. 2008). Achieving the right balance of nutrients for insects is also important to maximise growth (Griffin 2011). Nutrients that are not usually harmful can become toxic at excessive uptake levels (Griffin & Trewick). Food quality depends on the composition of the food, its presentation, and the life stage of the feeding insect (Grenier 2012). Some insects, for example, like to chew their food (Barrett 1991); other insects prefer live prey (Best & Beegle 1977). Two hypotheses exist for generalist herbivore feeding. The nitrogen limitation hypothesis claims that insects generally respond well to increases in nitrogen in their diet (Joern & Behmer 1998); the nutrient complementation hypothesis, however, claims a more varied diet is likely to provide a better compliment of nutrients (Joern & Behmer 1997). In an experiment on the grasshopper species *Chorthippus parallelus* (Zetterstedt) those given up to eight species of grasses had a higher survival and reproduction rate than orthoptera, which were only fed one plant species. However, when red clover, which has a high nitrogen content, was the plant fed to the grasshoppers that were allowed only one species of food, the consequences of low diet variability were significantly reduced (Joern & Behmer 1997). According to Cary (1983), The diet of tree weta consists of mainly plant material, but some species are omnivorous. Barrett (1991) reports that tree weta will eat leaves and fruit from *Coprosma robusta* (Raoul), carrots and insect protein such as houseflies and caterpillars. Moreover, Fisher et al. (2007) states that tree weta in their study feed on mahoe (*Melicytus ramiflorus* Forster) and broadleaf (*Griselinia littoralis* Raoul). Ground weta species will also ingest both plant and insect material. Wahid (1978) reported that diet analysis of *Hemiandrus* spp. found in apricot orchards revealed they eat thrips, collembolan, apricot flesh, and fungal spores. Additionally *Hemideina maori and Z. gracilis* both feed on coleopteran and lepidopteran larvae. However insect protein makes up a far larger part of *Z. gracilis* diet while *H. maori* is predominately an omnivore. Furthermore, in a DOC report, ground weta were found to ingest apple slices and leaves from mahoe and hebe plants (Barrett 1991). Moreover, Grant et al. (2006) reports that tusked weta in his study fed on fish flakes, *Coprosma* spp., oatmeal and corn kernels (Grant et al. 2006).

Feeding and nutrient requirements can differ depending on sex and stage. Grenier (2012) reports that nitrogen is particularly important for young nymphs and females. In a study by Unsicker et al. (2008), late instar females tended to eat grasses higher in nitrogen content. The authors suggest this is because females require more protein (Choe & Crespi 1997) to produce healthy egg batches. Juveniles have been shown to have a lower resource breadth. In a study by Sword and Dopman (1999), generalist grasshoppers tended to eat mostly plant matter as juveniles but more insects as adults. Hellmann (2002) postulate that this is because adults have the physiological capabilities to enlarge their habitat size. However, when provided with diet options in captivity, juvenile feeding may change. In a study by Griffin and Trewick (2011), juvenile weta eat more moths on average than adults. In a thesis study by Wahid (1978), the relatively poor fitness of weta reared on a synthetic diet was not because of nutritional quality, but due to the powdery form of the food; weta eat their food with mandibles and therefore need to be able to chew their food. Wahid (1978) also noted that weta fed on artificial diets containing mould inhibiter and ethanol as a solvent weighed significantly less than weta fed diets without mould inhibitor; the reduction in feeding may have been due to the toxicity of ethanol. Most insects will also require drinking water for survival (Wilson 2000). Barrett (1991) suggests providing water in the form of soaked cotton wool pads for weta.

Before ecological management methods in an applied setting can be sought, a better understanding of the behaviour of this weta species is needed. It is, therefore, necessary to determine conditions that maintain the health of *H. promontorius* because it is part of an endemic and iconic genus in New Zealand. The objective of this study was therefore to investigate whether container housing, habitat, and diet impacted weta performance. Performance in this thesis is evaluated in terms of survival rate (Unsicker et al. 2008) and growth (Broekhoven et al. 2015).

2.2 Methods for Trial One

2.2.1 Experimental design

Percentage survival and relative growth rate (RGR) of *H. promontorius* individuals subjected to habitat, diet, and container size factors were examined using a randomised, complete block design. The trial began on the 25th of February 2014. In total, 16 different treatment combinations were employed using a 4 x 2 x 2 factorial arrangement:

- Four diet treatments: two 'animal protein' diets (chicken; *Gallus gallus domesticus* Linnaeus and carrot; *Daucus*. *carota* Martens) and (blowfly pupae; *Lucilia sericata* Meigen and apple; *Malus domestica* Borkh cv. Granny Smith), a 'high carbohydrate diet' (wheat bran; *Triticum aestivum* Linneaus and mahoe; *Melicytus ramiflorus* Forster), and the 'varied diet' (consisting of all three previous diets).

- Two habitat treatments (varied) and (unvaried),

- Two container size treatments (one litre) and (two litre).

There were 12 feeding, 24 habitat and 24 container size treatment replicates resulting in 48 containers being used (Table 1). RGR and survival of individual weta were recorded after 28 and 56 days.

Table 1. Treatment numbers, diet, habitat and container size treatments used for laboratory maintenance Trial One. Diet type; chicken and carrot (CC) blowfly pupae and apple (BPA) wheat bran and mahoe leaves (WBM) and a diet consisting of the other three diet treatments (VD), habitat; leaves only (L) varied habitat consisting of leaves, twigs and a stone (V) container size; one litre (1) two litre (2).

Treatment number	Diet	Habitat	Container Size
1	WBM	L	1
2	WBM	L	2
3	WBM	V	1
4	WBM	V	2
5	BA	L	1
6	BA	L	2
7	BA	V	1
8	BA	V	2
9	CC	L	1
10	CC	L	2
11	CC	V	1
12	CC	V	2
13	VD	L	1
14	VD	L	2
15	VD	V	1
16	VD	V	2

2.2.2 Experimental protocol

Before capturing weta, habitat and container size factors within 48, 2 litre ice-cream (16.5 x 16.5 x 8 cm) plastic containers were prepared. To differentiate between container sizes, polystyrene card was placed in the middle of 24 plastic containers and held in place with duct tape (Fig. 3B). To prepare the lids, mesh was cut to overlap the container sides and 14 x 14 cm holes were cut in the plastic lids. The mesh was secured by rubber bands and the overlaying plastic lid. All plastic and mesh components were then sprayed with 70% ethanol as recommended by (Unsicker et al. 2008) to kill any bacteria that may be present. Although the ethanol was left for 30 minutes, parts were further rinsed with purified water to make sure ethanol was not present in the containers. Each container had roughly 1 cm of leaf litter spread on the bottom, and was then filled with 30-40 cm of organic soil. On top of the soil, leaf litter was sprinkled to a depth of approximately 1 cm (Fig. 3A). To separate habitat factors, two twigs and one stone were placed in each varied habitat treatment. Leaf litter and twigs were sourced from leaf litter underneath *Hebe* and kowhai (*Sophora* sp.) plants growing on Lincoln University campus. Stones were obtained from the borders of university roads and the soil was taken from an organic husbandry.

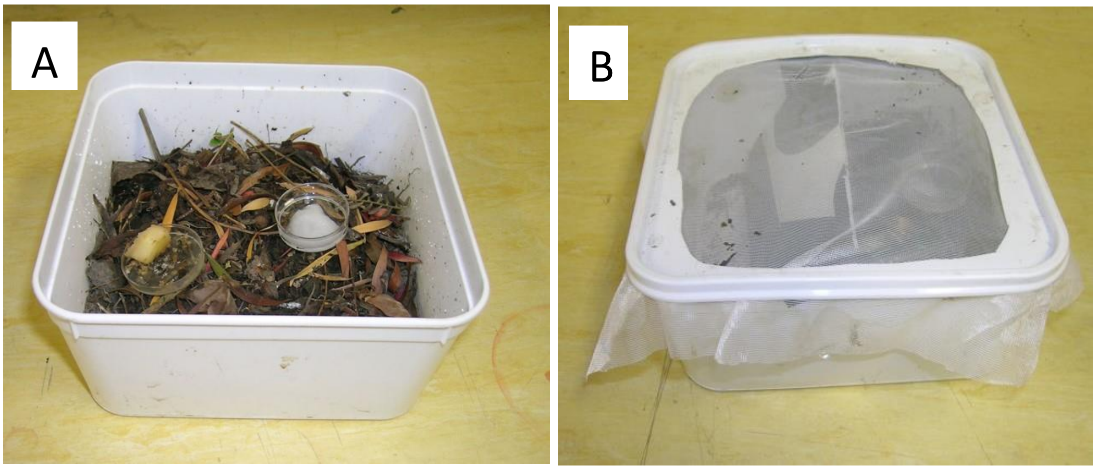

Figure 3. Two litre container bottom showing leaf litter on top of soil with a petri dish bottom containing a soaked cotton bud and a petri dish bottom with the diet treatment apple and blowfly pupae (A) and a 2 litre container bottom showing the plastic divider to impliment the one litre container size variable and also showing the mesh and plastic boundary lid (B).

Individual weta were caught on the Castle Cliffs vineyard in the Awatere Valley. To locate weta, the soil surface under vine rows was scraped aside to reveal where weta burrows resided. The burrows were then dug to a depth of approximately 30 cm. Weta holes were then prised apart. When weta were present, they were caught by hand and placed in a 70 ml vial. The vials contained cotton buds soaked in purified water and Awatere Valley soil. After transporting weta from the Awatere Valley to Lincoln University, individual weta sex, life stage, and weight were identified. According to Wyngaarden (1995), *Hemiandrus* sex and life stage can be identified by measuring and identifying body parts located on the abdomen. To accurately perform this task for all ages, weta would have to be killed or knocked out with CO_2. Instead, to identify sex and life stage weta were prised out of their containers with tweezers. A soft paint brush was then used to brush off the soil and plant material attached to the weta's body. Each weta was then placed in a clean plastic vial and weighed on a balance. Weta abdomens were then searched for signs of reproductive structures (ovipositors or paraprocts, which appear as pointed appendages protruding between the cerci (Van Wyngaarden 1995). If no reproductive structures could be seen, weta were deemed to be at the juvenile stage (Van Wyngaarden 1995). If any structure was visible, but weta weighed less than 0.5 g, weta were deemed to be in the mid instar stage. For weta weighing above 0.5 g, structures were checked to see whether they were seperated or touching. Males have only paraprocts, but in females, although they have paraprocts, they are obscured by valves which make up the ovipositor (Van Wyngaarden 1995). If the appendages were touching, they were deemed to be ovipositer valves, and therefore the weta was classed as a female. If they were separated, the appendages were classified as paraprocts and the weta was classed as a male (Van Wyngaarden 1995). Only adult weta were sexed.

Once covariates were recorded (sex, life stage, and weight), each weta was randomly assigned to a container resulting in only one weta per container. A 40 x 12 mm Petri dish lid containing a feeding treatment was placed in one corner of the container. The Petri dish bottom, containing a cotton bud soaked in purified water, was placed in the middle of the weta habitat (Fig. 3A). The four feeding treatments were, chicken and carrot (CC) blowfly pupae and apple (BPA) wheat bran and mahoe leaves (WBM) and a varied diet (VD) consisting of all the above treatments. The portions of each treatment were enough to fill the petri dish lids. Only two larvae were portioned to the blowfly and apple treatment. To fit all foods in the varied diet, slightly smaller portions of chicken, carrot and apple were given. However, it was never observed that weta ate any entire feeding treatment, indicating that the portions in the varied diet were sufficient.

Wheat bran and mahoe leaves were chosen because Joern and Behmer (1997) fed grasshoppers wheat bran in their trial, and mahoe leaves were reported by Barrett (1991) and Fisher et al. (2007) as a suitable food source for weta. Wheat bran was sourced from an organic supplier, and mahoe leaves were picked from plants on campus.

Chicken and carrot (CC) were selected due to their high availability and combination of carbohydrates and protein, which insects require in their diet. Additionally, Wyman et al. (2010) fed carrot to weta in their trial. The chicken used in this trial was canned in spring water, and the carrots were grown in a home garden without using any chemical sprays.

Blowfly pupae and apple (BPA) were chosen as Wahid (1978) and Carly (1983) report that weta species in the *Hemiandrus* genus have been found to eat insect protein. Wahid (1978) also reports that weta in captivity will eat apple slices. This combination of food type also offers a good source of carbohydrates and protein. The pupae were supplied from a commercial insectary, and the apple slices were sourced from an organic husbandry unit. A varied diet was included as a factor because Joern & Behmer (1997) reported that the grasshoppers in their trial bred more prolifically when a varied diet of grasses was fed to the grasshoppers as opposed to a single plant species.

Three times a week, Petri dish lids were cleaned with tap water. Fresh feeding treatments were then allocated to containers, making sure that the same feeding treatment always went into the same petri dish and same container. If the Petri dish bottoms were dirty, they were cleaned and the cotton bud was replaced. Regardless of replacing, the cotton buds were soaked with purified water. A fresh pair of gloves were worn when replacing each feeding treatment. During one of the feeding days, soil was also moistened with 50 ml allocated to the one litre treatment and 100 ml allocated to the 2 litre treatment. Additionally, if any fungi or herb species were found, they were removed from the containers.

The plastic containers were kept in a CT room with a 14:8h light: dark photoperiod, and set to 20°C. Three shelves were used as blocks, with each block containing only the 16 different treatment combinations. A thermometer was used to monitor temperature, a remote sensor instrument for relative humidity on top of the soil, and iButton sensors to record relative humidity in the soil.

2.2.3 Statistical analysis

To examine the effects of treatments on *H. promontorius* performance relative growth rate (RGR) and percentage survival were used. RGR takes into consideration the original weight of the insect when determining the insects growth rate over time (Bernays et al. 1997) and survival is a key demographic trait in orthopteran species that is often responsive to changes to diet and habitat changes (Joern & Behmer 1997). The formula for relative growth rate is:

Final weight (after trial) – minus original weight (before trial) /original weight (Bernays et al. 1997).

To analyse the RGR of weta, analysis of covariance (ANCOVA) models were created after the 28 day trial period (Bernays et al. 1997). Treatment factors included in the model were diet, habitat and container size, and a blocking factor. Covariates included in the model were sex, life stage, and original weight. Insignificant independent terms and interactions between factors were then taken out of the model (Marini et al. 2008). Proceeding this phase, if the remaining terms were not significant, variables were individually dropped from the model until the most parsimonious model was established (Bernays et al. 1997). Furthermore, analysis of variance was performed with only feed type in a model to see whether this term alone had any significant effect on weta RGR. No analysis of percentage survival was undertaken after 28 days because only three weta had died. However, due to a large proportion of deaths after two months, it was decided to record a dead weta's RGR as per the lowest RGR of a surviving weta. Thus, because the data was zero inflated, the RGR of weta were categorised (1= 0 - 0.24 , 2= 0.1 - 2.5, 3= 0.251 - 0.5, 4= 0.51- 0.8, 5= 0.81 – 0.22 g) to meet the assumptions of a GLM test. If a significant p-value was returned to $p \leq 0.0\ 5$ a Wilcoxon-rank-sum test was performed to establish between which treatments the significance lay (Nylin et al. 2000). A Wilcoxon test was used because of the non-parametric nature of the data (Lovric 2014). In addition, percentage survival of weta was analysed after 56 days with a generalised linear model (GLM) (Koricheva et al. 1998), whereby a binomial family was expressed with a log link transformation (Jorgensen et al. 2013). The same terms, were used for the GLM model as per the ANCOVA model used for RGR after 28 days. All analysis was performed in R Studio (RStudio 2012).

2.3 Methods for Trial Two

2.3.1 Experimental design and protocol

Container size had no significant impact on *H. promontorius* performance in Trial One. As space in CT rooms is at a premium in research centres, a further trial was developed to see whether containers with a smaller surface area had any impact on the percentage survival of weta. It was hypothesised that *H. promontorius* survival would only need enough soil substrate to build chambers, and to access food and water. For this trial, 12 x 6 x 6 cm (400 ml) containers were compared against two litre ice-cream containers to see if they influenced weta percentage survival after 28 days. A complete randomised block design was employed, whereby two replicates of each treatment compiled a block. The smaller containers had 1 cm of leaf litter at the bottom 9 cm of organic soil, and 1 cm of leaf litter on top of the soil. The two-litre containers had the same soil and leaf litter arrangement as unvaried treatments in the first trial. Petri dish lids and bottoms were placed in every container as per Trial One. However, chicken and carrot were exclusively used for feeding. The food was replaced twice per week (three and four days apart), and cotton buds replaced and soaked with purified water as needed. The temperature was kept within the same range as Trial One. Humidity was not measured, as the containers were too small for a remote sensor to fit inside. However, moisture levels were monitored by eye during feeding times and adjusted by either misting or forgoing watering the soil. Plastic lids were used to secure weta in all containers. Twenty 1 mm holes were made in the small containers with a hammer and nail. Ten 2 mm holes were made in the two litre container lid with scissors.

2.3.2 Statistical design

For Trial Two, A GLM was used with the same family and transformation as per the second month analysis for Trial One. However, original weta weight was the only covariate in the model. Sex and stage were not analysed because appendages on the abdomen of many weta were hard to distinguish. All analysis was performed in R Studio (RStudio 2012).

2.4 Results

Performing an ANCOVA model showed Weta RGR after a 28 day trial period was significantly influenced by block, diet , and original weta weight (Table 2). Factors container size and habitat independently and as an interaction did not significantly impact the predictability of RGR and were therefore dropped from the complete model. The drop1 function isolated the most parsimonious model to contain the terms diet (p < 0.05; d.f. = 3, F= 2.76) and original weight (p < 0.01; d.f. = 1, F= 12.36).

Table 2. Analysis of variance (ANOVA) table for weta RGR in laboratory maintenance Trial One from an ANCOVA with factors Block, Diet, Habitat, Container size (and the interactions of the last three), and covariates Original weight, Sex and Stage after a 28 day trial period ($R^2 = 0.665$).

Source of variation	d.f.	*SS*	*F*	*P* (>*F*)
Block	2	0.40	4.23	0.025*
Diet	3	0.48	3.38	0.033*
Habitat	1	0.00	0.00	0.996
Container size	1	0.01	0.17	0.682
Diet:Habitat	3	0.36	2.59	0.075
Diet:Container size	3	0.16	1.15	0.346
Diet:Container Size	1	0.02	0.52	0.481
Habitat:Containersize:Diet	3	0.14	0.99	0.411
Original weta weight	1	0.72	15.38	0.001***
Sex	1	0.12	2.71	0.111
Stage	2	0.01	0.13	0.878
Residuals	26	1.23		

df, degrees of freedom; ss, sum of squares; F, F-ratio; *P* (>F), probability (* $p \leq 0.05$; $p \leq 0.001$ ***).

Original weta weight had a negative estimate, that is, as original weta weight increased RGR decreased after 28 days over all feeding treatments (Fig. 4). In addition, original weta weight had the highest sum of squares and therefore the greatest impact on RGR. Moreover, an ANOVA model containing just RGR as a response variable and the factors diet, found diet to be not significant (d.f. = 3, p=0.10). This suggests that original weight had more of an impact on the predictability of weta RGR than diet.

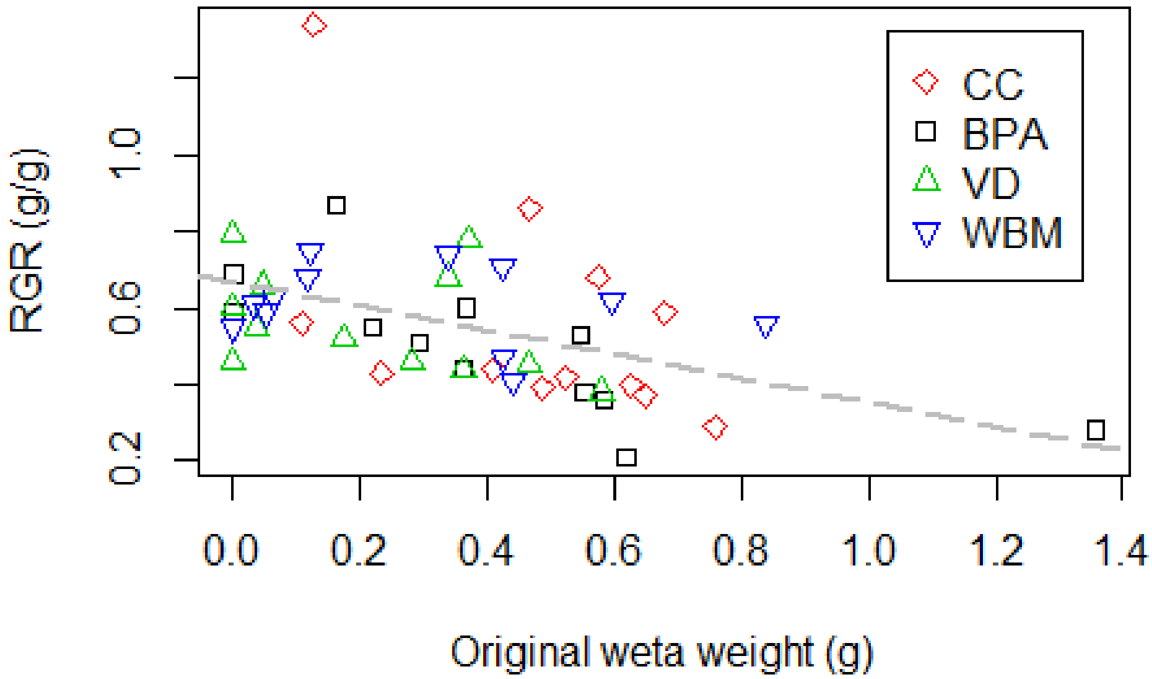

Figure 4. A linear line graph showing the negative slope relationship for laboratory maintenance Trial One between Relative growth rate (RGR; grams per 28 days / per grams) and Original weight of weta (grams) after 28 days from all four diet treatments.

When looking at the RGR means of weta diet treatments, 'animal protein' diets CC and BPA had a 0.2 g larger growth rate than VD and over a 0.1 g larger RGR than the 'high carbohydrate' diet WBM (Table 3). However, the feeding treatment with the highest percentage survival rating was WBM with 100% followed by CC with 92%.

Table 3. Relative growth rate (RGR) and % survival means of weta in laboratory maintenance Trial One subjected to different diet , container size, and habitat conditions after 28 and 56 days (CC= chicken and carrot, BPA= blowfly pupae and apple, VD= varied diet and WBM = wheat bran and mahoe leafs).

28 days			56 days		
	RGR (g/g)	% survival		RGR (g/g)	% survival
CC	0.47	92	CC	0.42	83
BPA	0.42	83	MWA	0.5	83
VD	0.22	83	VD	0.14	58
WBM	0.29	100	WBM	0.22	67
container 1L	0.34	84	container 1L	0.27	30
container 2L	0.36	95	container 2L	0.36	34
Unvaried Habitat	0.35	92	unvaried Habitat	0.28	67
Varied habitat	0.35	87	varied habitat	0.35	0.8

After 56 days, diet, original weta weight, and sex significantly influenced RGR categories of weta (Table 4). Subsequently only these terms were retained from the complete model. All three terms remained significant (diet: d.f. = 3, p=0.01; original weta weight: d.f. = 1, p= 0.05; sex: d.f. = 1, p= 0.01) .

Table 4. Analysis of deviance table using a GLM for weta relative growth rate categories in laboratory maintenance Trial One with block, diet, habitat and container size (and the interactions of the last three) as factors and original weta weight, sex, and stage as covariates after a 56 day trial period.

Source of variation	d.f.	X^2	*Pr* (>*chi*)
Block	2	0.62	0.575
Diet	3	7.34	0.005**
Habitat	1	0.12	0.640
Container size	1	0.79	0.236
Diet:Habitat	3	2.89	0.164
Diet:Container size	3	2.00	0.318
Habitat:Container size	1	0.92	0.204
Habitat:Container size:feed	4	1.28	0.520
Original weta weight	1	3.01	0.021*
Sex	2	3.68	0.010**
Stage	2	1.19	0.348
Residuals	26	15.68	

df, degrees of freedom; x^2, chi squared value; *Pr* (>*chi*), probability ($p \leq 0.05$ = *, $p \leq 0.01$ = **).

Due to the main factor (diet) showing significance, a post hoc Wilcoxon-rank-sum test was performed which showed weta RGR categories differed significantly between BPA and WBM (w = 69.5, p = 0.04) MWA and VD (w = 112.5, p = 0.01) and CC and VD (w = 96.5, p = 0.05). Looking at the RGR average categories, ‘animal protein’ diets CC and MWA sit in the category (0.26-0.5 g) while VD and ‘high carboydrate’ diet WBM hover around the (0.00 – 0.25 g) category (Table 3; Fig. 5).

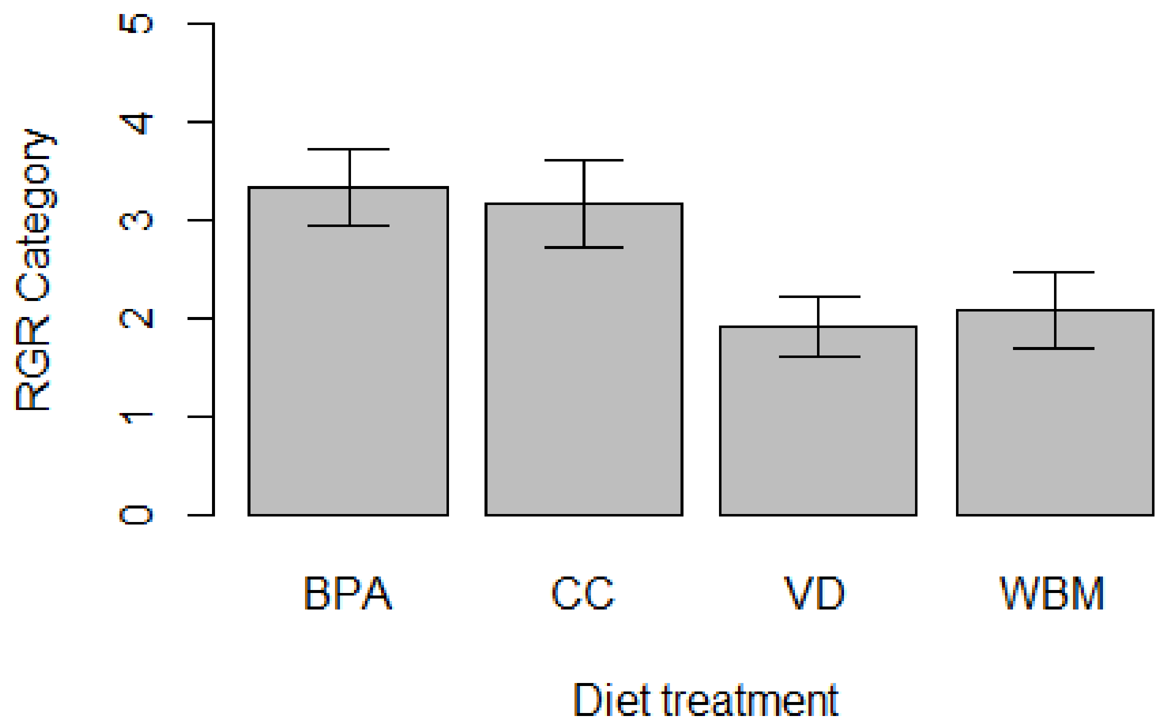

Figure 5. Weta RGR category averages in laboratory maintenance Trial One after a 56 day trial period when subjected to different food treatments (± SE). Averages are not adjusted for covariates. Categories; 1= 0 - 0.24 g, 2= 0.1 - 2.5 g, 3= 0.251 - 0.5 g, 4= 0.51- 0.8 g, 5= 0.81 – 0.22 g.

When performing a GLM after 56 days only the interaction between terms diet:habitat had any significance on the response variable percentage survival (x^2= 9.48, p = 0.02; Table 5). However when dropping other terms from the model, diet:habitat did not retain any significance (x^2= 11.12, p = 0.13). Animal protein diets CC and MWA continued to have at least a 0.2 g larger RGR after 56 days. Additionally, both these treatments had the highest percentage survival. Moreover, RGR and percentage survival was higher for varied habitat and two litre containers after 56 days (Table 3).

The only significant term in laboratory maintenance Trial Two on weta percentage survival after performing a GLM was container size (Table 6). Therefore both block and the covariate original weight were dropped from the final model (container size; d.f. = 1, x^2 = 10.35, p = 0.01).

Table 5. Analysis of deviance table using a GLM for weta % survival in laboratory maintenance Trial One with Block, Food, Habitat and Container size (and the interactions of the last three) as factors and Original weight, Sex, and Stage as covariates after a 56 day trial period.

Source of variation	d.f.	X^2	*Pr* (>*chi*)
Block	2	2.97	0.226
Diet	3	3.05	0.384
Habitat	1	1.09	0.296
Container size	1	1.12	0.300
Diet:Habitat	3	9.48	0.023*
Diet:Container size	3	4.87	0.181
Diet:Container size	1	2.95	0.085
Habitat:Container size:Diet	4	0.13	0.988
Original weta weight	1	0.42	0.516
Sex	2	1.85	0.395
Stage	2	0.01	0.926
Residuals	26	28.10	

df, degrees of freedom; x^2, chi squared value; *Pr* (>*chi*), probability (*p* ≤ 0.05 = *).

Table 6. Analysis of deviance table for laboratory maintenance Trial Two using a GLM for weta % survival With Container size as a factor and Original weight as a covariate after a 28 day trial period.

Source of variation	d.f.	X^2	*Pr* (>*chi*)
Block	1	1.72	0.189
Container size	1	6.20	0.012**
Original weight	1	3.03	0.081
Residuals	13	4.87	

df, degrees of freedom; x^2, chi squared value; *Pr* (>*chi*), probability (*p* ≤ 0.01 = **).

2.5 Discussion

Nitrogen influences Orthoptera performance more than most nutrients (Joern & Behmer 1997). This is largely because nitrogen plays a fundamental role in protein production (Bertram et al. 2008). Backing up this knowledge, weta fed BPA had a significantly higher RGR after 56 days than other treatments except CC, and there was a trend for grasshoppers fed 'animal protein' sources in the CC and BPA treatments to have both a lower death rate and higher RGR after 56 days than the 'high carbohydrate' diet WBM. Omnivore insects get a major part of their nitrogen needs from eating other insects (Schulze et al. 2001). Considering that insects are a considerable part of some ground weta species' diets (Cary 1983), it would make sense that protein is an important component in the diet of *H. promontorius*. Herbivore insects can obtain nitrogen from plant sources. However, Fagan et al. (2002) report that the predators of insects, on a relative basis of how many grams they weigh, tend to have 15 % more nitrogen reserves than herbivores.

Although nitrogen is important for all animal stages, Joern (1998) stresses the importance of nitrogen for juveniles and adult females in the reproductive phase. In this study, weta life stage and sex were not a significant factor in the model. However, the fact that weta with a lower original weight tended to have a higher RGR after one month suggests that younger weta may need a greater proportion of nitrogen relative to their size than older weta.

In this trial, WBM was the only treatment to consist exclusively of plant material. After 28 days, all weta fed this treatment had survived. However, after 56 days WBM had the lowest mean survival rate except for the VD treatment. This suggests that protein is an important component of a weta's diet.

Diet did not significantly impact the percentage of weta which survived after 56 days, however. Ground weta tend to have a generalist diet (Cary 1983; Barrett 1991; Van Wyngaarden 1995), and generalist insects appear to handle nutrient deficiencies better than specialist feeders (Raubenheimer & Jones 2006). Therefore, *H. promontorius* may have been able to handle lower nitrogen levels in the WBM treatment; alternatively, it is possible that *H. promontorius* was exhibiting compensatory feeding by eating more dry matter of a particular food source (Abisgold & Simpson 1987). In doing so, weta fed WBM may have been getting enough nitrogen to survive a 56-day period, but may not have survived another month of testing.

The varied diet treatment in this study consistently scored low in both mean death and mean RGR performance indicators, even though it consisted of four high-carbohydrate and two high-protein sources. It is possible that the combination of food in the varied diet masked the chemical signals of individual components; weta use odour as an indicator of food attractiveness (Bowie 2011).

Additionally the varied diet appeared to be wetter after a three day period and it maybe that juices from the chicken and apple reacted, creating a rancid odour.

H. promontorius death rate was significantly lower in the 12 x 6 x 6 cm (400 ml) containers when compared to two litre housing containers. All three container sizes, spanning both trials 1 and 2, provide sufficient depth to burrow, but they differ considerably in terms of above ground and below ground surface area. Weta do travel some distances above ground. For example, in their natural habitat, radio-tracked giant weta have been shown to travel 33 m per night on average (Watts et al. 2008); Wellington tree weta travel 11.9 m (Kelly 2006a), and the cook strait weta can travel up to 295 m (Empson et al. 2007). Although weta in the two-litre containers did not have to travel more than 30 cm in search of food, it was a comparatively larger distance than within the 400 ml housing units. Moreover, weta in the 70 ml containers were very restricted by the feeding and water-holding containers. Moving around or over these obstacles may have made food, water, and burrow access relatively stressful compared to in the two litre containers. Although no studies have looked at the effects of housing size on insect performance in captivity there have been experiments on the welfare of mammals kept in confined areas. For example, Pearce and Paterson (1993) report that smaller pen sizes increased stress levels in pigs in their study compared to larger pen sizes, ultimately leading to smaller growth rates. However, many experiments have compared the performance of insects when kept at different rearing densities. Although density-dependent effects cover more facets than just habitat area, it is worth noting the results because high density implies that species have less area to roam. Lance et al. (1986), for instance, showed that *lymantria dispar* (Linneaus) pupal weights declined as crowding increased; another study, by Peters and Barbosa (1977), showed that grasshopper lifespan shortened with increasing density levels.

Although no significance between treatments was shown for habitat, RGR and survival rate averages were higher after two months for a varied habitat. While twigs in the varied habitat did not enable much climbing, weta were able to experience a different terrain and obtain some elevation. In the wineries (Joanne Brady, personal communication, November 11th, 2014), and in native New Zealand forests, ground-dwelling weta do like to climb (Gibbs 1998). As with travelling along the ground, climbing may provide physiological benefits. Wild *H. promontorius* are commonly found under stones, usually when the soil is flooded. In this study's case, the stone may have provided another concealment option. Habitat variation, including patch diversity, has been proven to increase the abundance of certain insects within a landscape (Gathmann et al. 1994). Therefore, one can assume that habitat variation is indeed important. In addition, specific landscape structures can correlate with insect condition. For instance, Ostman et al. (2001)showed that the body mass of *Pterostichus melanarius* (Illger) was higher on farms which had a more varied habitat.

Weta sex proved to have a significant effect on RGR after the 56 day trial period. Although unanalysed, it would make sense that females RGR increased at a higher rate than males. This is because female orthopteran species tend to eat more in order to get a higher supply of nitrogen content to produce healthy egg batches.

During weekly observations, weta were found both on, and underneath, the leaf litter. Not only does leaf litter offer another concealing component for weta, but it also provides a softer walking surface. Barrett (1991) found that if weta travel along compacted soil, their tarsi can be damaged, which can lead to fungal infection in the damaged area. Therefore, although untested, leaf litter would appear to be a critical requirement for ground weta habitat.

Weta diet was only changed on Mondays, Wednesdays and Fridays. This meant that once per week, there was a three day period between replacing food. As a result, most of the food components lost a high percentage of moisture. Fowler et al. (2002) cut holes in lunchbox lids for ventilation, rather than using mesh lids. In contrast, my experiment kept only a one cm plastic lid boundary to hold the mesh in place. The mesh lid was used to help maintain humidity at around 80% as a pilot trial with holes in two litre plastic lids found relative humidity to be consistently around 95%. Because humidity, food moisture, and the air conditioning in the control room are interlinked, pilot trials are recommended to find the right balance. Monitoring moisture levels also helps to control spores and bacteria on natural diets (Sikorowski & Lawrence 1994). Since humidity was regularly monitored, none of the diets appeared to suffer any problems from microorganisms.

Laboratory maintenance of *H. promontorius* is a delicate process, considering its status as both a pest and a conservation concern. On the one hand, conservation is important, but exploratory testing is also required. Therefore, maintaining the performance of individuals used for testing is vital to ensure that results reflect testing on individuals in a similar state to when in their natural environment, and also so that multiple testing can be performed on the same insect. The results from this study suggest that container size, habitat, and diet are worth considering in the laboratory maintenance of weta. Additionally, future trials may test laboratory maintenance conditions for longer periods of time.

Chapter 3

Choice Tests

3.1 Introduction

An ecological management strategy is sought to control weta damage because of a growing awareness of the negative effects of insecticide application (New Zealand Wine 2014c) and the iconic status of weta in New Zealand (Cullen et al 2013).

As discussed in chapter one, trap cropping is one ecological method used to control pest damage on cash crops. Before trap crops are tested in the field, choice tests often take place in a controlled environment to isolate plant species which insects prefer (Badenes-Perez et al. 2004; Wallingford et al. 2013). Commonly, trap crop choice tests on insects are based around the oviposition or feeding selection of an animal (Badenes-Perez et al. 2004). The formats for the testing can be no-choice, (Peng et al. 2011) pairwise tests, or multiple choice tests (Badenes-Perez et al. 2004). Information from these trials aids in the selection of appropriate trap crop plants (Wallingford et al. 2013).

The objective of this study was to use feeding choice tests to identify suitable feeding plants for *H promontorius.* The hypothesis is that one or more plant species will be more attractive to *H. promontorius* than Sauvignon Blanc leaves and buds. The overall aim is to isolate one species which could be planted in a vineyard environment to test the effects on *H. promontorius* herbivory.

3.2 Methods

3.2.1 Non- vine plant species

Possible trap crop species, phacelia, buckwheat, alyssum and broad bean were compared in pairwise choice bioassays against Marlborough's most profitable vine variety, Sauvignon Blanc (Veseth 2008). All treatments other than Sauvignon Blanc were selected because they can handle frosts, and had previously been grown in vineyard environments. However, each trialled species had other beneficial traits. Buckwheat grows quickly, has proven palatable to other insects in a trap cropping systems, and attracts beneficial insects such as parasitic wasps (Blout et al. 2008). Phacelia will grow on many soil types, has shown potential as a trap crop, and attracts beneficial insects (Hickman & Wratten 1996). A previous study by Kogan (1998) proved *faba* beans to be highly attractive to adult leaf miners and therefore showed promise as a trap crop. Furthermore, broad beans have a large, robust seed that grows well in most agriculture environments (S. Wratten, Lincoln University, pers. comm). Alyssum has shown some promise as a trap crop for the diamond back moth (*Plutella xylostella*

Linnaeus) and attracts beneficial insects such as honey bees (*Apis mellifera* Linnaeus) (De Groot et al. 2005; Gonzalez 2014).

All alternative trap crop plants were grown from seeds in a glass house environment at Lincoln University. The glasshouse temperature was set to 25°C. Seeds were initially grown in a nitrogen mix within 200 ml potting containers. All healthy plants were subsequently transplanted into 500 ml pots when true leaves had formed.

3.2.2 Vine plants

To harvest vine buds, Sauvignon Blanc dormant canes were collected from Lincoln university vines in early April. Canes were cut off where the cane joins the cordon. Each cane was cut off into sections, roughly 5 mm above each node. The cuttings were then placed in holes in polystyrene trays so that the nodes remained upright. The polystyrene tray was then placed on top of a plastic container filled with tap water. The tray was placed in glasshouse at 15-20˚C. Within 4 – 6 weeks, bud burst occurred (Bennett 2008).

3.3 Insects

H. promontorius individuals were collected in two batches from a vineyard in the Awatere Valley, one in March and one in June. Both male and females were collected, consisting of juvenile, mid-instar and adult life stages.

3.4 Design and statistics

Feeding preferences of *H. promontorius* were examined using pairwise choice bioassays and a randomised complete block design. Statistical modelling was used to compare both:

- Sauvignon Blanc vine parts (Trial One = leaf, Trial Two = bud) and an individual non – vine treatment leaf in the same container, and
- between non-vine treatments across different pairwise bioassays

Due to the distribution of the data, comparisons of trap crop treatments were analysed with generalized linear models (GLM) using both binary (eaten or not) and quasipoisson (how much was eaten) distributions with a logit (Bailey et al. 2010) and log link function (Baltzer et al. 2007) respectively. As a result, 'the amount eaten' variable was estimated in whole numbers, because GLM only handle integers. Therefore if any part of a leaf or bud was eaten it was recorded as 1 cm squared. Otherwise the amount eaten was estimated to the nearest whole number. Weta weight, sex and stage were used as covariates to determine whether these variables influenced feeding. Additionally, blocking was incorporated in the GLM's. After establishing the complete model, insignificant individual and interaction terms were dropped from the model (Marini et al. 2008). If any of the remaining terms were insignificant, variables were dropped until the most parsimonious model was found (Kelly 2011). Furthermore, due to the GLM showing significance for non-vine treatment leafs in the Leaf and Bud Trial, Wilcoxon-rank-sum tests were performed (Guido & Gianelle 2001). These investigated: a) which treatments the significance lay between and b) whether the amount of non – vine treatment eaten was significantly more than the vine leaf eaten in the Leaf Trial. These tests could not be performed on the binary results as Wilcox tests do not handle binary data. Thus a McNemars test, which handles nominal data, was employed to analyse eaten/not eaten data in the Bud Trial to compare vine buds and non-vine treatments in the same bioassay (Brown et al. 1996). Treatments were considered significant if the reported *p* values were less than or equal to 0.05.

3.5 Experimental protocol

Two – choice preference experiments were conducted with *H. promontorius* in a controlled temperature room at Lincoln University. Temperature was set to 20 °C. Control containers suggest the relative humidity within the blocks ranged from 66-75%. All weta were individually weighed just prior to commencing the trial. The sex and life stage (juvenile, mid instar, adult) were also established as per the methods in the laboratory maintenance trial. For the Leaf Trial 68 two litre ice-cream containers were selected. On the bottom of the container leaf litter was sprinkled to a depth of 1 cm to help absorb moisture. Organic soil was then spread over the litter to a depth of 30 cm. On top of the soil, 1 cm of native leaf litter was again sprinkled. Each container lid had ten 2 mm holes to aid in ventilation and help control humidity. Young leaves were chosen for these experiments because they tend to have more sugars than older leaves and because anecdotal evidence suggests *H. promontorius* quits feeding on Sauvignon Blanc plants after three leaves have emerged from a bud. Leaves were deemed to be young if they had sprouted within a few days before the beginning of the trial. Previous choice test trials have used uniform leaf discs to test invertebrate feeding (Behmer & Joern 1993). Whole leaves were used in this trial due to the compound structure of phacelia leaves and the potential for increased volatiles to be released.

For experiment one a Sauvignon Blanc leaf was presented with a leaf of one of four possible trap plants in one plastic container. Each leaf was placed on moistened filter paper and randomly placed in one corner of the box. A cotton bud soaked in deionized water was placed in a 3 cm petri dish bottom and positioned in the middle of the box to provide water for drinking (Fig. 6). Once individual wetas were placed in containers, we randomly positioned four containers of each paired test on a shelf in the CT room. Each shelf acted as a block, controlling for microclimatic conditions. Feeding responses were estimated with a ruler and eye. Only one person conducted the measurements to increase the precision of the recorded data. Pilot trials weighing leaves (before and after) with a tripod scale and measuring leaf area (before and after) with a licor meter proved inaccurate. For experiment two a fresh batch of 48 weta were collected from the Awatere Valley. The same protocols were used for this experiment as experiment one, except instead of using vine leafs in the choice test, vine cuttings with a newly formed bud were used. A bud was used in the experiment once green material had begun to show, but leafs had not started to separate from the bud. Due to 48 weta being included in this trial there were 12 blocks in experiment two.

Figure 6. Two litre plastic container used in the pairwise choice test showing leaf litter on top of the soil with a vine leaf and a buckwheat leaf feeding choice for *H. promontorius* and a soaked cotton bud in a petri dish bottom for *H.promontorius* drinking.

3.6 Results

For the Leaf Trial, both non – vine plant species and original weta weight were significant terms in the non-vine comparison eaten/not eaten binary model (Table 7a). Non-significant interactions between terms and non-significant individual terms were dropped from the model. The most parsimonious model consisted of the response variable and the non-vine plant factor (d.f.= 3, X^2 = 10.96, p = 0.012). For the non–vine area eaten Leaf Trial, non – vine plant species, original weta weight, and block significantly influenced the GLM (Table 7a). After leaving these three terms in the model and removing the non-significant variables, all three terms remained significant (block: d.f.= 8, X^2 = 17.42, p = 0.042, non-vine plant species: d.f.= 3, X^2 = 15.19, p = 0.003, original weta weight: *d.f.*= 1, x2 = 6.68, p = 0.013). Subsequently, a Wilcoxon test was performed to compare different non-vine treatment factors, and found broad bean to have significantly greater cm^2 eaten than other non–vine plant species. However, there was no significance when comparing other treatment species (Table 8a; Fig. 7). Additionally, the non – vine treatment or covariates did not significantly influence the vine eaten or amount of vine eaten . Though, non–vine plant species did return a p value close to 0.05 significance for amount of vine eaten (p = 0.070; Table 7b). However, when comparing vine and non–vine treatments in the same Leaf Trial bioassay, a Wilcoxon-rank-sum test found broad bean to have significantly greater area eaten than vine leaves while the amount of alyssum leaves eaten was significantly less than vine leaves (Table 8b; Fig. 7). Furthermore, a McNemars test found broad bean to be eaten on significantly more occasions than vine buds (x^2 = 4.32, df = 1, p < 0.05), alyssum to be eaten on significantly fewer occasions than vine buds (x^2 = 5.04, df = 1, p < 0.05), and no significance for the amount of occasions phacelia and buckwheat were eaten compared to vine buds.

Table 7. Generalised linear model tables for the vine Leaf Trial, whereby non-vine leaf food treatments (broad bean, alyssum, phacelia and buckwheat) were paired in bioassays with a vine leaves. The response variables were eaten/not eaten (binary distribution) and amount eaten in cm^2 (quasi – Poisson). Terms tested for significance in the GLMs included food as a treatment factor, block as a factor, and life stage, sex, and original weight as covariates. Covariates were not considered for the Bud Trial. Table (a) describes non – vine treatment comparisons across different bioassays in the Leaf Trial, and table (B) describes vine leaf comparisons across different bioassays in the Leaf Trial. ($p < 0.05$ = *, $p < 0.01$ = **, $p < 0.001$***).

(a)

Binary model Leaf Trial –non-vine eaten/not eaten				**Quasi – poisson model** Leaf Trial non-vine Area eaten (cm^2)		
Terms	d.f	X^2	*Pr* (>*chi*)	d.f.	X^2	*Pr* (>*chi*)
Block	8	11.17	0.192	18	17.42	0.025*
Non – vine plant species	3	12.37	0.006**	3	15.19	0.001***
Stage	2	2.73	0.434	2	5.06	0.165
Sex	1	0.44	0.503	1	0.46	0.494
Original weta weight (g)	1	8.25	0.004**	1	8.46	0.003**
Residuals	34	26.81		34	30.63	

(b)

Binary model leaf Trial–vine eaten/not eaten				**Quasi – poisson model** Leaf Trial non-vine Area eaten (cm^2)		
Terms	d.f	X^2	*Pr* (>*chi*)	d.f.	X^2	*Pr* (>*chi*)
Block	8	4.46	0.812	8	7.17	0.606
Non – vine plant species	3	3.98	0.263	3	7.72	0.077
Stage	2	0.74	0.863	2	0.4	0.949
Sex	1	0.15	0.698	1	1.03	0.339
Original weta weight (g)	1	2.37	0.123	1	0.13	0.725
Residuals	34	53.21		34	53.21	

Table 8. Comparisons of cm^2 eaten by weta between pairs of non–vine plant food treatments across different pair-wise bioassays with vine leaves (a) and comparisons of vine leaf eaten compared to a non-vine food treatment in the same pairwise bioassay (b) using a Wilcoxon-rank-sum test ($p \le 0.05$ = *, $p \le 0.01$ = **).

(A) Non – vine leaf comparisons	Mean (cm^2)	*v*	*p*	**(B)** Vine leaf vs Non – vine leaf comparisons	Mean (cm^2)	*v*	*p*
Broad bean vs Alyssum	1.24 – 0.06	0.0	0.010**	Vine leaf vs Broad bean	0.35 – 1.24	2.5	0.020*
Broad bean vs Buckwheat	1.24 – 0.35	39.5	0.048*	Vine leaf vs Buckwheat	0.35 – 0.35	25.5	0.305
Broad bean vs Phacelia	1.24 – 0.35	55.0	0.050*	Vine leaf vs Alyssum	0.05 – 0.06	15.0	0.037*
Buckwheat vs Phacelia	0.35 - 0.35	8.0	1	Vine leaf vs Phacelia	0.35 – 0.35	10.5	0.480
Buckwheat vs Alyssum	0.35 – 0.06	0.0	0.173				
Alyssum vs Phacelia	0.06 – 0.35	1.5	0.200				

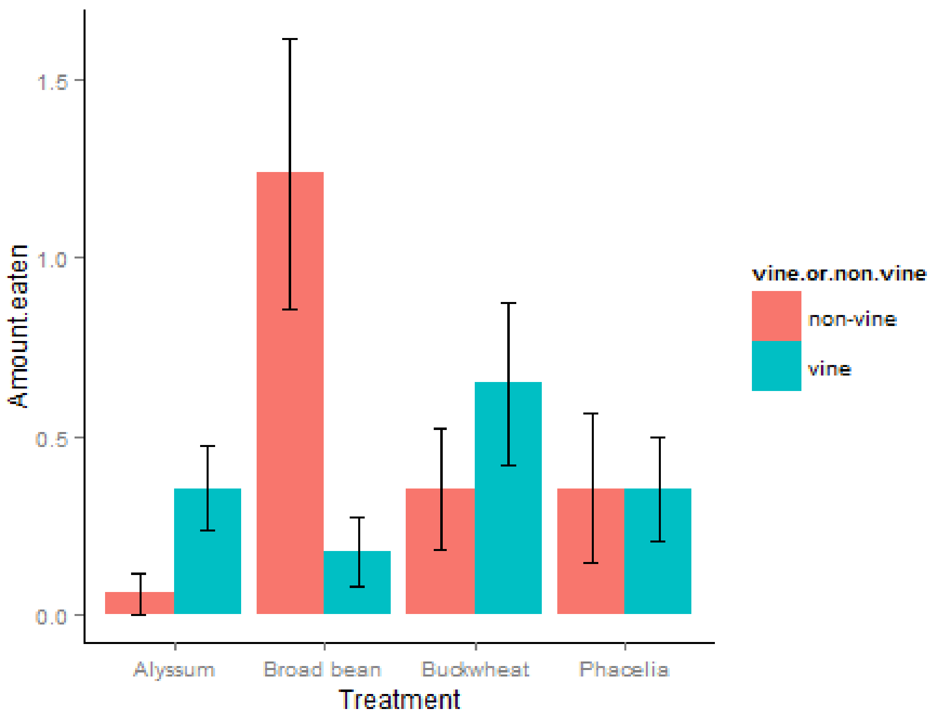

Figure 7. A comparison of the amount eaten by *H. promontorius* when a particular non-vine treatment was paired in the same container as a vine leaf (± SE).

In the non-vine comparison Bud Trial, the non – vine factor significantly influenced whether the non-vine treatment was eaten or not and how much was eaten respectively (p = 0.001, p = 0.001, Table 9a). A Wilcoxon-rank-sum test suggests broad bean was eaten significantly more than all other alternative treatments. Conversely, there was no significance between any of the other treatments for area eaten (Table 10). When analysing whether the bud was eaten, non-vine leaf did not influence whether the bud was eaten or not (Table 9b). However, when comparing vine and non-vine treatments in the same Bud Trial bioassay, a McNemars test found broad bean to be eaten on significantly more occasions than vine bud ($x^2 = 6.07$, df = 1, $p < 0.05$) and no significance for the other non-vine treatments compared to vine buds.

Table 9. Generalised linear model tables for vine Bud Trial, whereby non-vine leaf food treatments (broad bean, alyssum, phacelia and buckwheat) were paired in bioassays with a vine bud in the Bud Trial. The response variables were eaten/not eaten (binary distribution) and amount eaten in cm^2 (quasi – Poisson). Amount of bud eaten was not explored. Terms tested for significance in the GLMs included food as a treatment factor, block as a factor, and life stage, sex, and original weight as covariates. Covariates were not considered for the Bud Trial. Table (A) shows the results for non-vine comparisons across different bioassays in the Bud Trial and table (B) describes the comparison of vine bud eaten across different bioassays in the Bud Trial (p < 0.001***).

(A)

Binary model Bud Trial - non - vine eaten/ not eaten				**Quasi – poisson model** Bud Trial - non - vine cm^2eaten		
Terms	d.f	X^2	*Pr* (>*chi*)	d.f.	X^2	*Pr* (>*chi*)
Block	5	8.84	0.115	5	6.39	0.421
Non – vine plant species	3	16.75	0.001***	3	22.01	0.001***
Residuals	37	38.16		37	38.16	

(B)

Binary model Bud Trial - vine bud eaten/not eaten			
Terms	d.f.	x^2	*Pr* (>*chi*)
Block	5	8.14	0.148
Non–vine plant species	3	1.12	0.772
Residuals	37	43	

Table 10. Comparisons of cm^2 eaten by weta between pairs of non-vine treatment leaves across different bioassays with vine buds using a Wilcoxon-rank-sum test ($p \leq 0.05$ = **).

Non – vine leaf comparisons	Mean ($cm^{2)}$	*v*	*p*
Broad bean vs Alyssum	2.08 – 0.33	0.0	0.005**
Broad bean vs Buckwheat	2.08 – 0.54	45.0	0.008**
Broad bean vs Phacelia	2.08 – 0.54	45.0	0.008**
Buckwheat vs Phacelia	0.54 – 0.54	7.5	1.000
Buckwheat vs Alyssum	0.54 – 0.33	3.5	0.710
Alyssum vs Phacelia	0.33 – 0.54	4.0	0.408

3.7 Discussion

Of all the potential trap crop plants used in this trial, broad bean appears to be the most suitable candidate for *H. promontorius*. Broad beans were more likely to be eaten compared to other non – vine treatments, and the amount of broad bean leaf eaten was much higher. In addition, broad bean was the only non-vine plant to be eaten significantly more than a vine plant in a bioassay. Furthermore, the amount of broad bean eaten, when paired with a vine bud, was significantly more than other non- vine treatments paired with a vine bud.

Broad bean has previously been shown to be highly attractive to leaf miners in choice tests with snow pea (*Pisum sativum* Linneaus). Moreover, a field study using broad beans as a trap crop for snow peas found that the number of larvae emerging from snow peas in the monoculture control was much higher than in the crops with a broad bean margin (Edwards et al. 2014). However, in a study by Smith (2013), there was no difference in thrip *(Thysanoptera: Thripidae*) counts between snow pea with a broad bean border and snow pea monocultures. This illustrates that broad bean may only work as a trap crop in specific environments.

Beans are normally used in an IPM system to become nurseries for the natural enemies of pest insects. For example, a trial on apple orchards in Massachusetts found that 21 species of parasitic wasp were attracted to the nectar of broad bean (Bugg & Waddington 1994). Additionally, experiments on apple orchards in New Zealand found that broad beans increased the numbers of *Dianella tasmanica* (Hook) captured in sticky traps (Berndt et al. 2000). Moreover, broad bean is commonly infested by aphids, which in turn attracts parasitic wasps. Landis et al. (2000) reports that, by cutting the beans, the parasitic wasps then switch to attacking pests on hop plants. This indicates that broad beans could provide multiple ecosystem services, including acting as a trap crop and luring beneficial insects.

However, as there was no significant influence of broad bean, buckwheat or phacelia on the amount of vine eaten, further testing in a controlled environment may be needed before selecting one or two species for trials in an applied setting. This is especially relevant because individuals were given the choice of only two alternatives, rather than the full range used in the experiments, meaning that individuals may have become habituated to their choice plants over time, providing false positive results. If the trial was set up as a multiple choice test, with all non–vine treatments offered to each weta, then it would be easier to rule out habituation (Simpson 1994). Heard (2000) reports that habituation in plant-eating insects is common, because most plant compounds act as deterrents but are non-toxic to their hosts. Furthermore, the lack of air flow in the ice-cream containers may have caused olfactory cues to be weak, or perhaps have allowed aromatic compounds from one plant species to mask the smell of the paired plant (Bernays & Eigenbrode 1997).

Chapter 4
Distribution trial

4.1 Introduction

Burrows are essential to ground weta because they allow them to hide from predators, avoid some harsh weather conditions, oviposit, and rear young nymphs (Lukhwareni 2013). Ground weta spend most of their time in their burrows; particularly females, who are tending to hatchlings and eggs (Chappell et al. 2014). *Hemandrius* spp. may stay in their chambers for consecutive days (Smith et al. 2013), exiting only to forage and mate at night (Stringer 2006). When they venture above ground, ground weta rarely travel more than two metres from the burrow (Chappell et al. 2014). Additonally, Gibbs (1998) reports that adult tusked weta probably remain faithful to their chambers. Consequently, the selected burrowing site must offer favourable biotic and abiotic conditions within a relatively small area.

Gravid orthopteran females have the responsibility of selecting an oviposit site. Thus, females have to consider many different environmental cues before making a choice. Selecting for food avialability is relatively straight forward (Mbata 2004); orthopterans reportedly use sensilla on their antennae and mandibles to choose between diet options (Laverack et al. 1976). However, ensuring the oviposition chamber has favourable conditons is a more complex assignment. Soil conditions tested for include chemical and physical properties such as texture, consistency, pH, and moisture content, as well as microclimate qualities, temperature and humidity (Hunter-Jones 1972; Uvarov 1977). To test soil quality, gravid orthopteran females may use their ovipositor, abdomens, antennae or palps. These bodily parts have either sensory organs or sensilla, which act as mechano- or chemoreceptors to provide information on soil chemical and physical properties (Mbata 2004). For example, gravid tettigoniids and acridids use their ovipositors and abdomens to test for soil properties. The process involves tapping the soil, test-digging, and inserting their ovipositor into the soil. Several test-digs may occur before ovipositing at a site (Woodrow 1964). Mbata (2004) reports that L. M. migratoriodes will not deposit eggs in an exploratory dig if conditions are not favourable. *Hemiandrus promontorius* have long antennae (up to 1.5 times their body length), sizeble mandibles, and no sense of hearing. Therefore it is plausible that sensilla on their mandibles and antennae play an important role in sensing olfactory cues from plants and protein sources.

Conditions for females to oviposit are not universal within orders, or even within a genus. The American migratory locust, for example, searches for alkaline soils, while the red locust (Nomadacris septemfasciata, Audinet-Serville) will reject saline soil (Mbata 2004). However, studies have shown that a combination of burrow characteristics can determine ovipositon sites and differences between egg pod numbers. For instance, Gong et al. (2008) reported that sites without egg pods and sites with egg pods varied significantly in vegetation cover, sun index, and soil moisture at 5 cm depth. Furthermore, Mbata (2004) reported that the model which best predicted egg pod number contained organic matter, K, P and plastic index variables.

There are limited studies on oviposition preferences for ground weta. However, distribution studies by Wahid et al. found that sites with a higher proportion of sand and lower proportion of clay were preferred for texture. Weta preferred sites that were wetter than the mean, but not saturated. The least preferred sites were in areas with slight depressions. The author postulates this is because water funnelled down into the depressions, increasing the chances of flooded burrows (Wahid 1978). Additionally, studies by Wyngaarden (1995) found the Tekapo weta (*Hemiandrus* new sp.) only inhabited sites with silty soil. The authors believe this is because ground weta require fine substrate soil to construct burrows.

The objective of this study was to investigate the distribution of *H. promontorius,* on vineyards in the Awatere Valley, in relation to different habitat variables. We hypothesised that at least one of the variables tested would influence relative weta density. The aim of this study was to gather data which could potentially predict variations in weta population density and the potential damage they might cause. This would give vineyard staff an idea of when weta outbreaks may occur and what conditions could be manipulated to prevent outbreaks.

4.2 Methods

4.2.1 Study site

The study was conducted in six different soil types at Castle Cliffs, Caseys Road, and The Favourite vineyards in the Awatere Valley, between the 14th – 18th of July (winter trial) and between the 29th of September and the 3rd of October (spring trial) (Table 11).

Table 11. Soil types and vineyard locations for the distribution trial.

Soil type	Vineyard
Shallow sandy loan	Castle Cliffs
Deep silt loam	The Favourite
Stoney sandy loam	The Favourite
Deep silt	Castle Cliffs
Sandy	Castle Cliffs
Templeton	Caseys road

4.2.2 Sampling method

A vine block planted on each soil type was randomly selected from one of the three vineyards for sampling between the 15th and 18th of July. The same vine block was again sampled between the 29th of September and the 3rd of October. Within in each block, two rows were randomly selected for sampling between each sampling period. Sampling occurred on the southern edge and centre of a row. The edge for this experiment was considered to be the first three bays of a row; the centre was the distance between bays 6 and17. The distance between each bay is 7.5 m (Fig. 8). All three bays were sampled in the edge, and five random bays were sampled in the centre. Underneath the vines, the middle point in a bay was chosen for digging. Opposite these points, a hole was also dug in the middle of two rows. A spade was used to dig approximately a 25 by 25 x 30 cm hole in the soil. The soil was sifted to check number of weta per dig sample (weta density). Weta were collected and placed in 70 ml plastic containers filled with soil and moist cotton buds for drinking water. After checking for weta, soil was collected from each hole that was dug for laboratory analysis and sealed in a plastic bay to avoid moisture loss. In order to keep the soil samples cold during field work and transport, they were kept on ice (Hill et al. 2009). The samples were subsequently transferred to a refrigerated room until analysis took place (Ferreira Araujo et al. 2013). Additionally, a penetrometer was used to test the resistance of soil down to a depth of 15 cm. Mullins et al. (1994) reports that penetrometers are used to record soil compaction and resistance to root growth. Penetrometer readings were taken within 50 cm of the dig spots, but never closer than 5 cm.

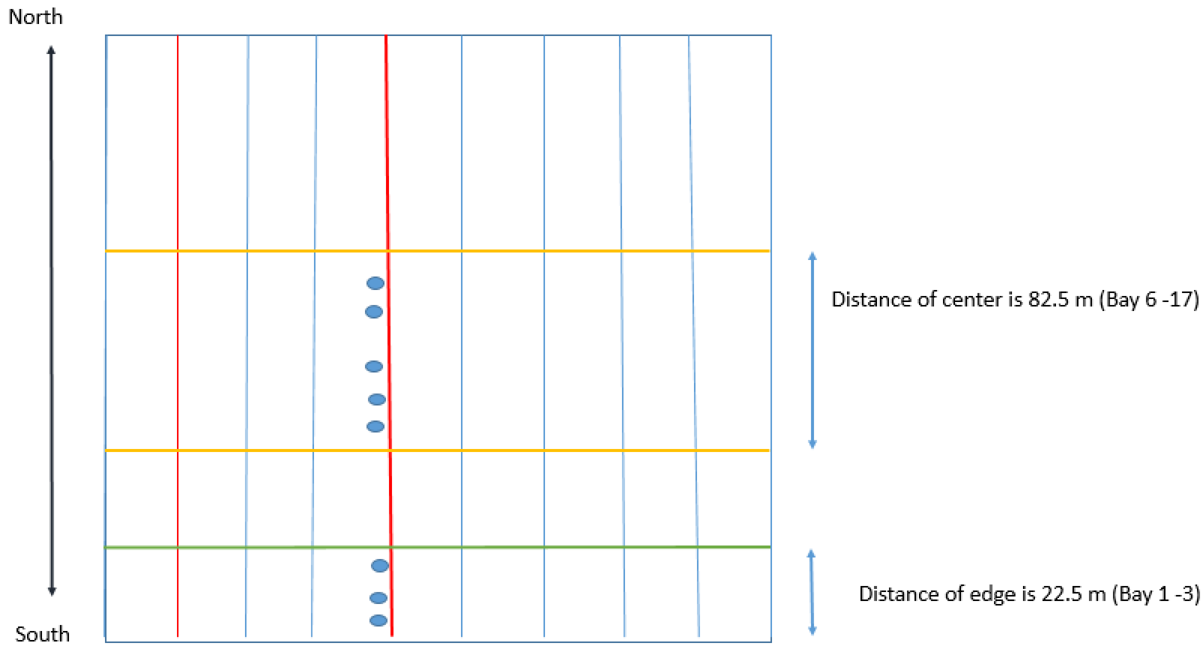

Figure 8. Example of a vine block (blue lines) showing two random rows selected (red lines) with three dig holes at the edge (edge is southern blue line up to the green line) and 5 random dig holes in the centre (centre is the area in-between the yellow lines).

4.2.3 Establishing weta weight, sex and age

Weta sex, stage and weight were established as per the methods described in the laboratory maintenance trial.

4.2.4 Properties tested

Soil moisture, pH, soil organic matter and position of burrow were selected as properties to test in the winter trial. The soil pH was selected to test because it was proven in a trial to be the most important soil quality in determining egg pod number for the armoured ground cricket *(Acanthoplus speiseri* Brancsik) (Mbata 2004). Soil moisture was chosen because it was positively correlated with burrow site selection for orthopteran species (*Locusta migratoria manilensis* Meyen) (Bao-Yu et al. 2006), and because anecdotal reports suggest that *H. promontorius* prefers wetter parts of vineyards (Joanne Brady, personal communication, March 10th, 2014). Organic matter was decided upon as a soil characteristic to test, because it is proven to increase the soil holding capacity (Bot 2005) of soil, and therefore could influence the preference of burrowing sites. Moreover the position of burrow (underneath or in-between vine rows) was selected because anecdotal reports suggest weta prefer burrowing underneath vines; therefore replicated studies are needed to quantify these observations. In the spring trial pH and organic matter were not tested because of time constraints.

To determine moisture percentage of soil, 10-20 g of soil was measured into a crucible and dried in an oven at 105°C for 24 hours.

Calculation: Weight of moist soil (g) ÷ weight of oven-dry soil (g) = moisture factor (Blakemore et al. 1987).

Percentage of soil organic matter was determined by placing the oven dried sample into a muffle oven (500 °C) for five hours. Organic content of the sample was estimated as follows:

Calculation: % Loss of ignition = (weight after ignition ÷ oven dry weight) X 100 (Blakemore et al. 1987)

To record soil pH, soil from one of the bags was spread out on a plastic tray and dried in an oven at 15 °C for 48 hours. The soil was then crushed and sieved. Ten grams of soil was then measured into a 70 ml vial. Additionally 25 g of deionised water was dispensed into the vial and then shaken. The solution was then left overnight before measuring the pH with a meter (Gomez-Garrido et al. 2014).

4.3 Statistical analysis

Linear models were established for analysis of both winter and spring data. The winter model included the response variable weta per dig sample (weta density) and explanatory variables soil type, location, organic matter percentage of soil, moisture percentage of soil, pH and penetration resistance. In the spring trial, pH and organic matter were not tested in the linear model because of time constraints. All analysis was performed in R Studio (RStudio 2012.).

4.4 Results

The winter distribution trial found that average numbers of weta per dig sample (weta density) were only significantly influenced by the position of dig samples when performing a linear model with all measured variables (Table 12). After dropping insignificant terms, position remained significant in the final model ($p < 0.01$; d.f. = 1, F= 12.91). Weta density in the winter trial was significantly higher underneath a vine row compared to dig samples between vine rows (Fig. 9).

Table 12. Analysis of variance table comparing the influence of explanatory variables (Soil type, Position, Organic matter % of soil, moisture content % of soil , soil pH, and penetration resistance of soil (kPa)) on the response variable (average number of weta per dig sample (weta density)) during a winter distribution trial.

Explanatory variables	d. f.	*SS*	*F*	*P (>F)*
Soil type	5	0.17	25.48	0.148
Position	1	0.36	259.73	0.040*
Organic Matter %	1	0.05	37.38	0.100
Moisture content %	1	0	0.89	0.518
pH	1	0	3.79	0.300
Penetration resistance (kPa)	1	0.04	28.82	0.117
Residuals	1	0.01		

df, degrees of freedom; ss, sum of squares, F, F-ratio; *P* (>F), probability ($p \leq 0.05$ = *).

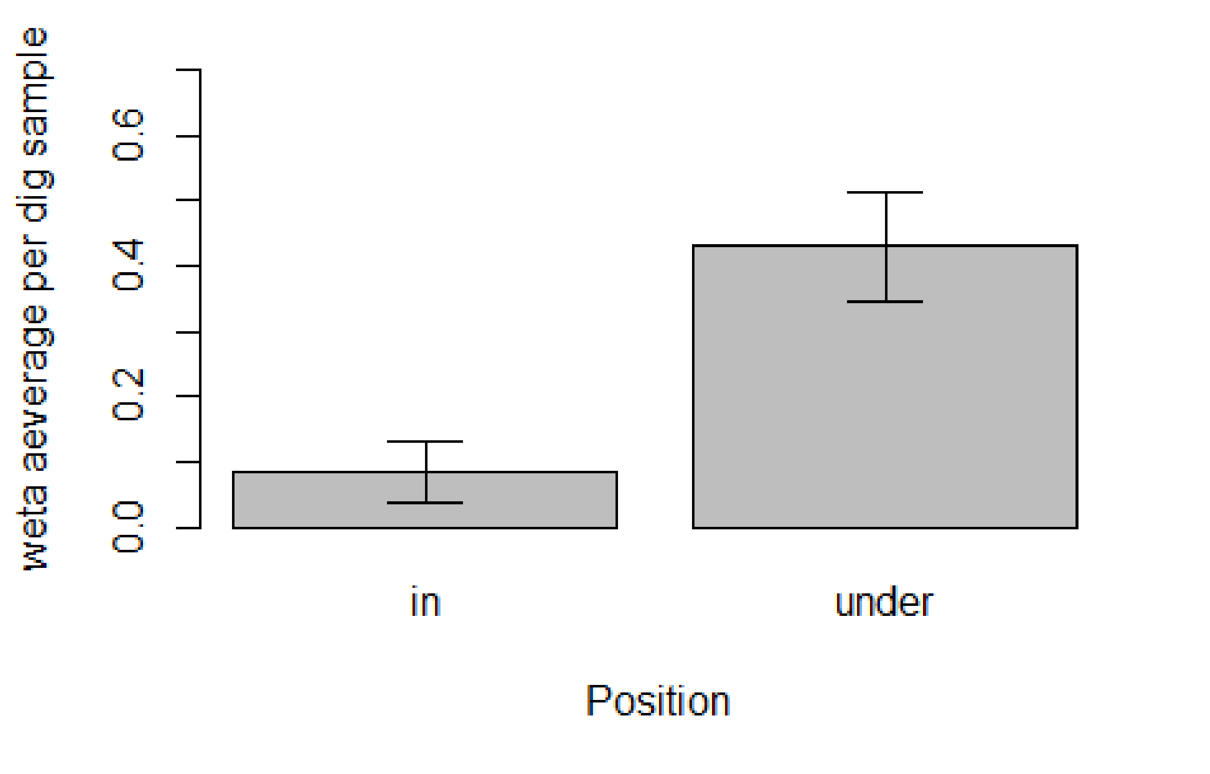

Figure 9. Average number of weta per dig sample (weta density), at each of the two position points sampled during the winter distribution trial (± SE; in = in-between two vines rows, under = directly underneath a vine row).

A Linear model with all explanatory variables gathered from the spring distribution trial showed soil type, penetration resistance, position, and moisture content percentage to significantly impact weta density (Table 13). Subsequently, a linear model was produced to show the effect of dig position (in-between rows or underneath a row) on penetration resistance, which showed a significant linear relationship ($p < 0.0006$; d. f. = 1, $F = 24.1$). Average penetration resistance is a lot higher in-between the rows as opposed to underneath a vine row (Fig. 10).

Table 13. Analysis of variance table comparing the influence of soil type, position, moisture content % of soil, and penetration resistance (kPa) on the average number of weta per dig sample (weta density) during a spring distribution trial.

Explanatory variables	d.f.	*SS*	*F*	*P* (>*F*)
Soil type	5	0.22	15.74	0.023*
Position	1	0.15	54.76	0.005**
Moisture content %	1	0.13	45.32	0.006**
Penetration resistance (kPa)	1	0.99	344.8	0.001***
Residuals	3	0.01		

df, degrees of freedom; ss, sum of squares; F, F-ratio; *P* (>F), probability ($p \leq 0.05$ = *, $p \leq 0.01$ = **, $P \leq 0.001$***).

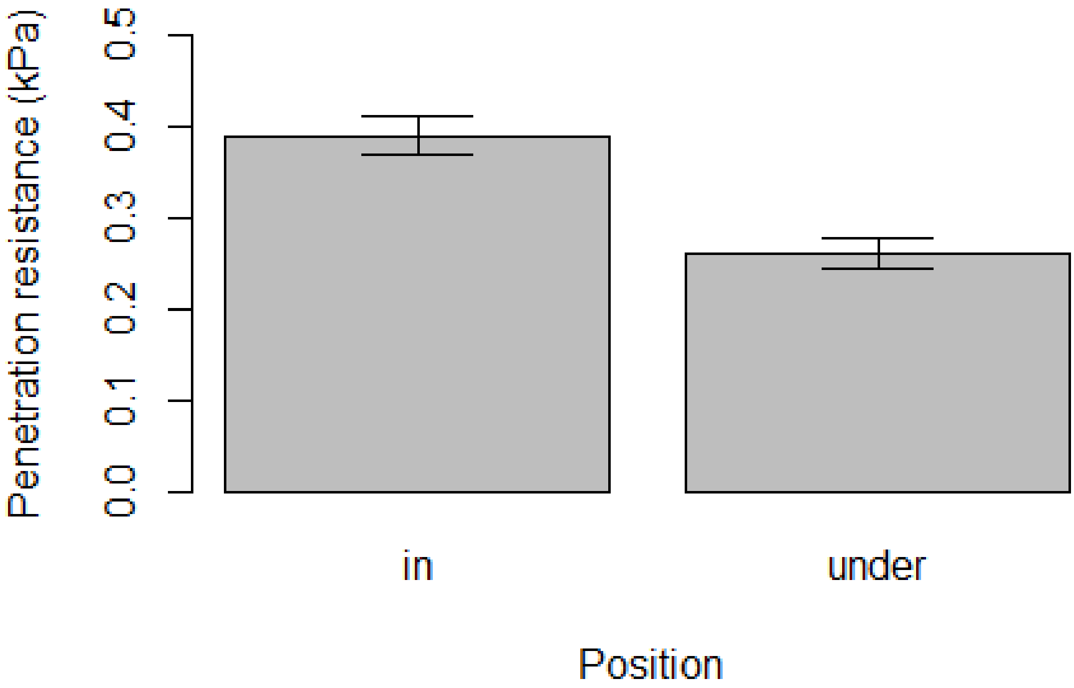

Figure 10: Penetration resistance averages (kPa) for the spring trial at the two different positions that penetration was recorded. (± SE; in = in-between two vine rows, under = directly underneath a vine row).

4.5 Discussion

Soil resistance increases as soil becomes more compact. Consequently, it is harder for biological species to penetrate through compacted soil layers (Landolt et al. 2014). For example, in a study by Montagu (2001), broccoli leaf area was correlated with the capacity of roots to penetrate different levels of compacted soil. This trial suggests that, just like plants roots, weta find it difficult to penetrate compact soil. Unlike plants though, weta are mobile and can test soil properties before choosing a burrow site. Therefore, if given a choice within their natural mobility range, weta appear to choose soil with less resistance in the Awatere Valley. Choosing less dense soil to excavate a burrow would clearly require less energy and less time to be out in the open, and decreases the chance of body parts being damaged during the process.

The results of the spring trials showed that soil penetration was significantly lower underneath the vines. This would be expected because irrigation only occurs underneath the vine trunks and the increased water content will decrease soil mechanical resistance (Masle 1998). However, ease of excavating burrows may not be the only reason that weta choose soils with less resistance. Compacted soils also have less pore space, meaning oxygen levels decrease (DeJong-Hughes et al. 2014). Considering weta spend the majority of their life in their burrows, a steady flow of oxygen for gas exchange would appear to be vital. Additionally, smaller pore spaces make it difficult for water to filtrate down through soil layers, and although not as significant as penetration in the complete spring model, moisture content did appear to influence weta numbers. Moisture content is important not only to decrease the penetration resistance of soil, but also to keep eggs moist, and to prevent burrows from drying out (Wardhaugh 1980). In a study by Hertl et al. (2001), there was a significant linear relationship with crickets ovipositing in response to burrow moisture levels. Too much water flooding burrows can, however, be harmful to weta, causing anaerobic conditions and making gas exchange difficult (Natural Resources Conservation Service 2014). Therefore gravid females need to select soil with a structure capable of allowing water filtration without being to porous.

Only the position term showed any significance in determining weta numbers in winter. However, as weta nymphs emerge from their egg cases in the spring season (Ramsay 1978), the higher weta numbers made it easier for generalised models to locate significance for specific variables in the spring trial. Additionally, weta are more difficult to locate in winter because they burrow deeper during this seasonal period (Peter Johns, personal communication, March 8th, 2014), presumably to aid in protecting eggs and decreasing the risk of burrows being flooded. As a result, winter data does not give a true reflection of the weta population on vineyards in the Awatere Valley. Organic matter did return a value close to significance in the winter trial, though, and if tested in the spring trial, this variable may have proved to be significant. Organic matter increases the water holding capacity of soil and in doing so, influences the moisture levels and structure of the soil (Bot 2005). As a result, although no studies have correlated organic matter percentage of soil and weta density, it would make sense that organic matter may be an important component in determining where weta choose to excavate their burrows.

Chapter 5
Policy analysis

5.1 Introduction

The drowning of New Zealand land during the Oligocene period, a lack of land-based mammal predators, and the isolation from other continental land masses for 80 million years, meant New Zealand's biota developed unique characteristic and became naturally depauperate (Gibbs & Potton 2006). More recently, the arrival of man 800-1000 years ago had a huge impact on NZ's biodiversity through the release of mammalian predators (such as rats and stoats), habitat destruction, and hunting of native fauna (Landcare research 2014). Although NZ continues to lack fauna richness, the uniqueness of many native animal species means New Zealand is often referred to as a biodiversity hotspot (Goldberg et al. 2008). As a result, protecting the distinctiveness of New Zealand's fauna is important for ecosystems and earth's biodiversity.

Many of NZ's native and endemic species are considered iconic (Hibbard 2014). Often, these species exist at very low population levels, meaning they are difficult for the public to view, for example the Maui dolphin (Forest & Bird 2011). Some iconic animals around the world exist in large enough populations to become pests to large factions of society. A well-documented example is the grey wolf, which is both a lucrative tourist attraction (Yellowstone Park 2014) and a perceived threat to farmers' livestock and hunters' prey in the United States (Washington Department of fish and Wildlife 2011). Iconic pests with resource purposes create management issues. On the one hand, reasonable population levels of the species need to be maintained for conservation and resource benefits. On the other hand, businesses need to be protected from the damage the species causes. Studies analysing the policy behind iconic pest – resource animals such as kangaroos can be readily found (Grigg 1988; Hercock & Tonts 2004; Waitt 2014). However, studies analysing lessons learnt from a managed iconic pest and how successful strategies controlling this pest could be applied to a recently established pest-resource are non-existent.

The first aim of this research was to identify New Zealand native fauna species that had been managed for at least a decade as an iconic pest - resource species. The lessons learnt over an extended period of time on how to manage this iconic pest may be helpful in attempting to manage weta on vineyards.

The second aim of my research was to get an idea of where vineyards in the Awatere Valley stand in terms of conservation efforts, how keen managers are to do more conservation work on their vineyards and what conservation obstacles vineyards face in terms of protecting *H. promontorius* populations so they do not become threatened in the future. This information may also help to plan conservation and management strategies to be implemented on vineyards, with a focus on implementing control techniques to preserve natural populations of iconic animals on NZ vineyards and potentially elsewhere.

5.2 Methods

A set of guiding criteria were created to aid in identifying a relevant New Zealand native animal species which is considered iconic, has positive and negative economic consequences, and which has been managed over a number of years. These criteria were defined by the research team. A literature review encompassing peer-reviewed papers, reports, and internet articles was undertaken to identify ten iconic NZ fauna species and to evaluate each species against the criteria. A species which met all the criteria was then selected. A qualitative policy analysis of the selected species was then conducted by way of an open-ended questionnaire with a government manager and a businessperson, who have had to control the selected pest (Owen 2014). Subsequently, a comparison between the nature, pest attributes, and opportunities of the selected species and weta was undertaken. This involved a literature review to aid in determining the potential applicability of the selected species management strategies for weta (Neuman 2006). The second form of open-ended questioning entailed interviewing five different vineyard managers to isolate qualitative trends, and differences in vineyard conservation policy (Owen 2014). All managers interviewed for this chapter did not have their given names attached to their answers. Instead mangers are referred to as a number from one to five. Information from all interviews was then summarised and suggestions were made as to what vineyard policies were successful for conservation, and what policies could be trialled on vineyards to conserve weta populations while still maintaining production efficiency (Nikolenyi et al. 2003).

5.3 Results

Before an iconic species was nominated, a set of criteria was determined to judge NZ animal species against. Kea policy was then researched through interviews and vineyard managers were interviewed on their own company's parcel of land.

5.3.1 Criteria and the species assessment

Iconic: A species that lives permanently or migrates to New Zealand and has special individualistic traits and/or is well known or unique to New Zealand.

Tourist attraction: A species which is used in marketing New Zealand, and/or attracts a high proportion of overseas and New Zealand visitors to view it.

Negative economic consequences: Significant economic damage to businesses.

Positive economic benefits: Significant monetary benefits for businesses.

Controlled: Management systems have been or are still in place to monitor and regulate pest populations.

Managed for ten years: Management systems have been in place over a ten year period to control what is considered a pest species and an iconic species.

Threatened or at risk: The individual species is listed in the NZ threat classification system in either the Threatened or At Risk categories.

5.3.2 Assessment of species against criteria

Ten of NZ's most iconic species were selected for analysis, to determine if they had pest-resource characteristics and other features which could inform the current research on weta in vineyards. The NZ fur seal (*Arctocephalus forsteri* lesson), for example, is a tourist attraction in Kaikoura (Sealswim Kaikoura 2014), but is not considered threatened (Department of Conservation 2005). The kiwi (*Apteryx australis* Shaw), Tuatara (*Hatteria punctate* Gray), Yellow-eyed penguin (*Megadyptes antipodes* Hombron), and humpback whale (*Megaptera novaeangliae* Borowski) are tourist attractions (Iconic Tours Dunedin 2014; University Herald 2014; Whale watch 2014; Willowbank 2014), give positive economic spinoffs, and are threatened, but they have no significant negative economic consequences (Table 14). The Paradise shelduck (*Tadorna variegate* Gmelin) owes its iconic status to its distribution in City Rivers and it may have some economic benefits as a game bird. However it has no significant positive economic impacts and, in fact, is controlled through special hunting permits when pest populations blossom on NZ farms (Fish & Game New Zealand 2014b) (Table 14). The Maui dolphin (*Cephalorhynchus hectori maui* Baker) has such a threatened population (Department of Conservation 2014c) that no form of tourism can be based around their viewing. The white pointer shark (*Carcharodon carcharias* Linneaus) has positive and negative economic impacts within NZ, has a threatened status, and is a tourist attraction. However, it is not controlled as a significant pest species in New Zealand. The kea (*Nestor notabilis* Gould) has been managed as a pest- resource species since 1986; it is valuable for tourism but causes economic damage to some farmers. Additionally, the kea's inquisitive nature makes it a pest on skifields and high country eateries, where it hunts for rubbish and can damage vehicles (New Zealand Birds Online 2013). The kea has been protected since 1986, but previously thousands of kea were legally hunted because they injured and killed sheep (Rudge 2006). The combination of human bounty hunting and introduced mammalian predators has reduced kea populations to the point they are now considered nationally endangered (Table 14), (New Zealand Birds Online 2013).

Table 14. The 10 selected iconic animals found in New Zealand which were assessed against the identified criteria, plus weta assessed against the criteria as well (* = represents the species meets that criteria on). 1= (Department of Conservation 2014b), 2 = (Shark Dive NZ 2013), 3= (Hayes 2014), 4=(Sharks-World 2014)5= (STQRY 2014), 6= (Department of Conservation 2014a) (7) = (Simmons & Fairweather 1998) 8= (STQRY 2014) 9= (Akaroa District Promotions 2014) 10=(Coventry 2004), 11=(Department of Conservation 2010), 12 = (Forest & Bird 2011), 13 = (Department of Conservation 2011), 14 = (Department of Conservation 2011), 15 = (Iconic Tours Dunedin 2014), 16 = (Department of conservation 2014h) 17= (University Herald 2014) 18 = (Otorohanga Zoological Society 2011) 19 = (Cox 2014), 20 = (Willowbank wildlife Reserve 2014), 21 = (Fish & Game New Zealand 2014a), 22 = (Morton 2014), 23 = (Trip advisor 2014), 24 = (Whale watch 2014), 25 = (Department of Conservation 2014i), 26 = (Environmental Protection Agency 2004) 27 = (Department of Conservation 2014f), 28 = (Willowbank 2014), 29 = (Orr - Walker 2014)30 = (Rootsweb.ancestry.com 2014) 31 = (Department of Conservation 2014j), 32 = (Bradley 2012), 33 = (Trust 2014), 34 = (Zealandia 2014)35 = (Department of Conservation 1998)36 = (Department of Conservation 2014d), 37 = (Bowie 2012), 38 = (Department of Conservation 2014e), 39 = (Joanne Brady, personal communication, March 5th, 2014), 40 = (Van Wyngaarden 1995)

Species	**Iconic**	**Tourist attraction**	**Negative economic consequences**	**Controlled**	**Manage For 10 years**	**Positive economic benefits**	**Threatened or at risk**
White pointer	* (1)	* (2)	*(3)			*(36)	* (4)
NZ fur Seal	* (5)	* (6)				*(7)	*17
Weta	* (37)	* (38)	* (39)	*(39)		* (38)	* (40)
Kea	* (27)	* (28)	*(29)	*(30)	* (30)	* (32)	* (33)
Hectars dolphin	* (12)	* (9)				* (10)	* (12)
Maui dolphin	*(11)						* (12)
Tuatara	* (31)	* (28)					*(35)
Humpback whale	* (23)	* (24)				* (25)	* (26)
Yellow eyed penguin	* (13)	* (15)				*(14)	*(16)
Kiwi	* (17)	* (18)				* (19)	* (20)
Paradise shelduck	*(21)		*(22)	*(21)	* (21)		

5.3.3 Comparison of kea with weta

Kea and weta are both iconic animal species that are only found in NZ. The inquisitive and gregarious character of kea make them popular with tourists (Smith 2014) and their problem-solving capabilities have gained them worldwide recognition (Auersperg et al. 2011). Weta , on the other hand, owe their iconic status to their distinctive look, ancient lineage, and large size for an insect (Goldberg et al. 2008). Furthermore, there is overseas interest in weta, largely due to appearances in BBC documentaries (BBC 2014). While both kea and weta can be considered pests, kea damage is much more widespread. For example, kea have been known to injure sheep on high country farms throughout NZ's South Island (Kea conservation Trust 2014), whereas significant weta damage is currently only reported in the Awatere Valley on vineyards (Joanne Brady, personal communication, March 5th, 2014). In addition, although not substantiated in any economic reports, the benefits to NZ's economy from the kea would appear to be greater. For example, the kea is used in advertising campaigns at airports throughout NZ, tourism campaigns, and it lends its name to leading NZ brand "Kea – campers." Although weta are connected with the branding of NZ's leading digital company "weta work-shop," they a play a relatively minor role in contributing to NZ's economy.

5.3.4 Kea management

Kea have been managed as a pest since the late 1800s. Initial controls which continued until the 1970s consisted of kea being legally shot without permission needed from a government department (Orr - Walker 2014). As a result, kea were classified as vulnerable in the 1970s by the IUCN (Morelli et al. 2012). Kea manager 1 believes that a crucial step in conserving an iconic pest species is giving protection to the species before the population becomes threatened; a pest species may continue to be hunted at a lower level even after it is afforded protection, due to the difficulty of changing public attitude towards a pest species. Kea "were first protected in 1986, but some farmers attitude towards kea when they became protected didn't change." This situation is similar to others worldwide, such as in Australia, where the majority of sheep farmers still consider kangaroos as pests even though scientific research suggests otherwise (Ben-Ami et al. 2012).

An additional reason for providing early protection for an iconic species is because it is easier to garner support from businesses and government. According to kea manager 2 "Once you have protection for a species, businesses are likely to rethink their pest management strategies, and governments are more likely to fork out money to preserve the species." These thoughts are echoed by Green et al. (2014), who state that once conservation laws are in place, companies are more likely to comply with the law and fund environmental projects, because shareholders will be privy to the law and demand more social responsibility.

A negative mentality towards pest species makes conservation of an iconic pest species difficult. Kea manager 1 reports that it is crucial to change the paradigm of business owners. “Instead of seeing iconic pests as a burden, think of them as an opportunity, and remember they were in the environment before your business began”. Vineyard manager 1 suggests that iconic pests can be used as a marketing tool to gain a competitive advantage. Examples may include advertising conservation efforts to manage an endemic insect, and providing tours which enable customers to encounter the iconic species and to view conservation strategies on the vineyard or farm. Sebastiano and Vincenzo (2009) report that a burgeoning tourism sector exists in wine-producing communities around the world where consumers are wanting to not only taste good wine but also experience the culture and values of the wine community. Additionally, a report by Jenkins (2009) suggests that corporate social responsibility can allow companies to exploit niche markets and gain a competitive advantage over other companies.

Contextualising the pest impact to a specific situation can provide better management outcomes than doing a large-scale study over different areas because the same pest species often causes different levels and types of impact in different areas. Kea manager 1 recommends that conservation groups and governmental departments contextualise pest damage for two reasons: firstly, so that individuals are aware that you understand the business has to be profitable; secondly, so that control methods can be altered to suit the specific scenario which increases the chances of a successful result. Kea manager 1 reports that, “if scientists turn up to their business and speak to them face to face, they are more likely to understand your control suggestions and try different control methods and also perhaps farmers haven’t thought of an easy and good solution.” This theory is reiterated by Jenkins (2009) who suggest that a collaborative approach between managers and scientists may be a more efficient way to connect scientific knowledge with management action. In their study, the collaborative exchange of information and meetings between fisheries management and scientists meant that conservation policies were more effective at managing brown trout populations in the French Alps than in the past.

Education is seen as an important step to encourage all age groups to undertake action to support conservation practices (Ballantynea et al. 1998). However, Kea manager 1 believes that educating younger generations is especially important when attempting to conserve an iconic species; older generations are less likely to see a benefit in compromising production for the sake of conserving a pest species. In a report by Reid and Scott (2007), the authors take it one step further by suggesting that educating younger generations on conservation issues may help children alert parents and other adults, who would ordinarily not be open to an environmental discussion, to think about how their habits are impacting the environment.

According to (Freeman et al. 2004) companies need to shift from solely a shareholder perspective to meeting the obligations of other stakeholders. Kea manager 1 supports this argument, believing that an important aspect in pest conservation is to get companies directly affected by an iconic pest to have conservation as one of their targets: “It is important to get companies to look at their overall image; protecting wildlife should be part of their goals and image, and therefore some profits should go back into the conservation of species.”

Designing an appropriate control method that fits in with business operations and is effective at controlling a pest is challenging. Norton et al. (1999) suggests a collaborative approach to pest management, whereby the needs and thoughts of different interest groups are expressed to scientists and each other from the beginning, and shared regularly throughout the design process. This way, there is more opportunity for stakeholders to appreciate each other’s concerns (Norton et al. 1999). Kea manager 1 and 2 also suggest stakeholders exchange information before the implementation of control methods. Kea manager 1 stated that, “scientists can exchange ideas with businesses; perhaps farmers haven’t thought of an easy and good solution”. Equally though, kea manager 2 said it is important that conservationists design strategies that fit the production model of a business.

5.3.5 Vineyard managers perspectives

The questions posed to vineyard managers, although open-ended, enabled answers to be summarised into yes or no categories (represented in Table 15). Every manger interviewed expressed the view that productive grape-growing land on their vineyard was to be used for producing wine, and not for conservation purposes. All managers additionally responded that they would prefer more native plantings and biodiversity within their vineyard boundary (Table 15). For example, Vineyard manager 4 said that, “native plantings add more variety to what is essentially a monoculture farm, and attract biodiversity which makes working on the vineyard nicer and is good for the environment.”

Table 15. Answers received from vineyard managers from a range of open-ended questions summarized into a yes or no format (Y = yes, n = no).

	Vineyard manager 1	Vineyard manager 2	Vineyard manager 3	Vineyard manager 4	Vineyard manager 5
Enough workers to implement conservation areas on vineyard	n	Y	y	n	n
Person dedicated to landscape conservation	n	y	n	n	n
Human resource person helps organize conservation staff and capital	n	Y	n	n	n
Conservation is part of the company's culture	n	y	n	n	n
Production comes first	y	y	y	y	y
Manager would like to have more biodiversity on vineyard	Y	Y	Y	Y	Y
Only plant in unproductive areas e.g. headlands	y	y	y	y	y
Like having native plantings on vineyards	y	y	y	y	y
Involve conservation stakeholders in conservation areas on their vineyard	n	y	y	y	y
Prepared to involve conservation stakeholders in conservation decisions on vineyard	y	y	y	y	y
Prepared to explore ecological ways other than plastic sleeves to control weta	Y	Y	Y	Y	Y
Use sprays to kill other major insects e.g. leafroller	Y	Y	Y	Y	Y

The number of vineyard staff numbers per hectare are not the same across all vineyards in this trial, as Table 16 shows. Vineyard managers 2 and 3 both had the most workers per hectare, with one worker per 30 hectares (Table 16). Additionally, both managers answered that they have enough workers to implement conservation projects on most of their unproductive vine-growing land. However, whereas vineyards run by manager 2 had most of their headlands planted with native plants, wildflowers and wetlands, manager 3 had a poor representation of conservation-specific areas. Vineyard manager 3 stated that, “often conservation projects start off well but are neglected or sprayed; it is best to pool money together and concentrate on projects on land outside of vineyards.” Vineyard manager 1 had the least number of workers per hectare on his vineyard, with one worker per 40 hectares (Table 16).

Table 16. Staff on the vineyard per number of hectares.

Vineyard manager 1	**Vineyard manager 2**	**Vineyard manager 3**	**Vineyard manager 4**	**Vineyard manager 5**
1/40	1/30	1/30	1/35	1/35

Staff numbers being problematic were reiterated further, when managers were asked what the biggest hindrance is on their vineyards. All three vineyards which had less than one worker per hectare thought that staffing issues were the biggest production issue outside of the strong Pacific winds they experience in the afternoon (Table 16, 17). Vineyards 1 and 3, which had one worker per 30 hectares, thought that water and pest issues respectively were their biggest production issue besides afternoon Pacific winds (Table 17).

Table 17. The biggest hindrance to productivity on the vineyard, besides the afternoon wind which comes off the Pacific coast.

Vineyard manager 1	**Vineyard manager 2**	**Vineyard manager 3**	**Vineyard manager 4**	**Vineyard manager 5**
Staff	Water	Pest	Staff	Staff

Of all the managers, only vineyard manager 2 expressed that conservation values are a strong part of the company’s ethos: “We are expected to follow strong conservation policies, and applying for money from the big bosses for conservation projects is usually not a problem.” On the other hand, vineyard manager 1 said that, “caring for the environment is relatively non-existent in our company.”

Vineyard manager 2 was also the only vineyard manager to have a dedicated landscaper for conservation projects, and the only vineyard to state that a human resources employee helps to organise the logistics of sourcing workers and capital to implement environmental projects: "We come up with the conservation idea and the human resource manager sources the equipment and if need be the extra labour to implement the conservation project."

All of the managers said their companies were currently working with research institutes. However, most of the research is centred on experimenting with synthetic agrochemicals, as the majority of pests on a vineyard are controlled with chemical sprays. All vineyards would be prepared to research the use of ecological engineering on their vineyard, if they thought there was a reasonable chance that EE could provide a long-term benefit. In fact, vineyard manager 4 reported that EE should be a compulsory component in tertiary vine-making courses: "In my viticulture classes, very little was taught about sustainability and natural resource controls."

Every vineyard would additionally be keen to work with other stakeholders (schools, councils, conservation groups) to help implement conservation projects.

5.4 Discussion

5.4.1 Kea and weta comparison significance

Both kea and weta are iconic species that are recognised around the world as unique and highly-valued animals. Additionally, both species are sometimes considered pests. As a consequence, conservation strategies must find a balance between business interests and maintaining a healthy population of both the kea and weta. While kea can be pests in a number of different environments, *H. promontorius* is only known to cause significant economic damage on vineyards in the Awatere Valley. As a result, it would appear that management strategies for weta could be mastered on an individual vineyard, and exported to other vineyards without too many changes required. However, as stated by kea manager one, contextualising the conflict between the business owner and conservation interests is vital if business owners are going to apply ecological control methods. Therefore, assessing each vineyard would not only evaluate the vineyards as a unique environment but also establish an understanding between conservation groups and the business manager.No study has been undertaken to compare the comparative contributions of kea and weta to the NZ economy. However, given the high profile given to kea in tourism marketing, and the fact it is the world's only mountain parrot, suggests it might generate more economic returns than weta (a proposition that could be tested, but not in this research).

5.4.2 Potential policies for businesses to increase conservation on vineyards

Although all managers would like to have more biodiversity on their vineyard, it is clear that implementing conservation areas is secondary to profit margins. An example exists on manager 5's vineyard, where a lot of time is taken up with training inexperienced staff, and there are fewer workers per hectare than on manager 2's vineyard: "I would love to build ponds and areas for the next door vineyard's falcons to utilize, I just don't have the time or an extra worker," "It's not as though I don't have enough unproductive land for conservation projects." If manager 5 was to have an extra worker, and/or higher wages were spent on hiring skilled workers, perhaps more conservation projects would be established. A comparison can be made with vineyard 2, whereby almost all their headlands are planted to promote biodiversity. The fact that vineyard 2 has more workers per hectare, a skilled landscape gardener for conservation projects, and a skilled human resource manager, appears to make conservation projects more easily completed. In order for vineyard 2 to implement the scale of conservation projects it has, though, significant amounts of money need to be spent. The opportunity cost is direct investment in grape production, thus it would seem, as is the case with vineyard 2, that conservation has to be a part of a company's culture. The importance of having wildlife conservation as part of a company's goals and image was reiterated by kea manager 2, who believed a proportion of a company's profits should be allocated towards conservation. Vineyard 3 appears to back up this logic, because having conservation as part of the company's culture meant they spent more time and money on implementing conservation projects on unproductive land than the other vineyards interviewed in this chapter. Jenkins (2009) agrees that companies need to infuse conservation in their culture, suggesting there may be a competitive advantage to conservation efforts, but for conservation investments to be established, an ethical culture within the company must first be established.

According to my results, most companies use broad-spectrum chemicals to kill pest insects such as leaf rollers. However, chemicals commonly used on vineyards, such as pyrethrin, also kill beneficial insects such as butterflies and hymenoptera species (United States Environmental Protection Agency 2013b). In the case of an iconic insect like the weta, using plastic sleeves as a control method is certainly better than spraying, but other potential methods for weta such as trap cropping would not only reduce the use of petrochemicals in the production of plastic sleeves but could also attract beneficial insects such as bees and hoverflies. Therefore, although Vineyard 3 showed conservation was a part of its company's culture, it does not consider EE as a first priority for controlling pests. However, if companies were to market EE control methods and conservation strategies, as suggested by kea manager one, then perhaps the negative paradigm around pests could be changed to create a competitive advantage. Marketing environmentally friendly vine products, through such things as certificate logos on vine bottles, has proven to provide a competitive advantage in some markets (Atkin et al. 2011).

5.4.3 Potential policies from governmental and conservation groups to protect iconic pests

Businesses and individuals experiencing pest damage don't always have the knowledge and time to control pests using natural resource methods (Allen et al. 2002). Therefore, left to their own devices, companies will often use sprays, as in the case of the five vineyards involved in this study. Kea manager 1 and 2 both expressed that scientists and other stakeholders are critical in formulating a situation that balances conserving an iconic pest and maintaining business profits. With more knowledge involved in decision making, solutions that may have been overlooked could prove to be effective and cheaper. If DOC staff and research institutes were allowed to explore and study weta damage, not only would talking directly to vineyard managers help scientists understand the vineyard business models, but it would also allow scientists an opportunity to design management strategies specifically for an individual vineyard.

Teaching younger generations about the significance of endemic and iconic species is critical in encouraging continued developments in biodiversity (McWilliams, 2001 #229}. Perhaps, as suggested by vineyard manager 4, EE principles could be made compulsory in farming and vineyard degrees. Additionally, students could be taught to use iconic pests such as weta as a marketing tool to attract customers.

Corporate social responsibility, on some interpretations, does not require businesses to go above and beyond their legal responsibilities (McWilliams & Siegel 2001). Therefore, if *H. promontorius* had legal protection, companies would be forced into devising control methods that minimise impact on weta. This would make it more likely that wine companies would team up with research institutes to improve their understanding of EE control. An example of a vineyard company teaming up with research teams exists with this project, whereby EE principles are being researched to control *H. promontorius* damage on vineyards.

Chapter 6

Conclusion

6.1 Conclusions and future research

The overall aim of this thesis was to investigate the pest status of *H. promontorius* and assess possible approaches to mitigate its effects on vines without using insecticides. This approach was developed because of the iconic status of weta and the desire to manage it in a 'sustainable' way. In the process of investigation, the following objectives were achieved:

1. Establishing favourable laboratory maintenance conditions for *H. promontorius*

2. Deciphering a potential trap crop to reduce herbivory on vines

3. Determining distribution patterns for *H. promontorius*

4. Isolating policy strategies for weta conservation

Objective 1: Laboratory maintenance results and suggestions for future research

The results, as predicted, suggest that weta growth rates increase if they are fed a high protein diet. While survival rate was not significant after 56 days for the diet variable, the results suggest that if the trial was run for longer, high-protein diets may significantly increase survival. The blowfly pupae and apple diet had the highest mean survival and RGR category after 56 days, although not significantly greater than the chicken and carrot treatment. This is interesting because the proportion of insect protein in the BPA diet was much lower than the proportion of chicken in the CC treatment. Perhaps if *H. promontorius* were fed four blowfly pupae instead of two, there would have been a significant difference between both high-protein diet treatments. Although the varied diet consisted of the highest proportion of protein, the combination of all foods was not appealing to weta. It may be that the varied diet produced chemicals which masked the odour of more appealing foods in this treatment.

Weta performance was also impacted by container size. As temperature and humidity were kept more or less constant for all treatments, and there was sufficient space to burrow in all treatments, it would appear that the container treatments did not differ significantly in abiotic conditions, but in their capacity to allow weta the physiological benefits of ranging around the container.

As mentioned in Chapter 2, the physical differences between habitat treatments only consisted of a stick and a stone in the varied habitat. Tthis lack of physical differences most likely explains why the habitat variable had no significant effect on weta performance.

Future research on the laboratory maintenance of weta should establish the conditions which increase weta survival rates. This would aid further research where weta need to be kept for longer periods of time. Additionally, habitat treatments need to allow for the behaviour weta exhibit in the field. In this trial, weta could only climb one cm above the soil surface on a twig provided in the varied habit treatment. However, *H. promontorius* is known to climb at least one metre above the ground on shrubs and vine plants.

Objective 2: Choice test results, and suggestions for future research

Although from an ecological perspective, a range of plant species is desirable on a vineyard, from a business perspective planting just one trap crop species is more efficient and less costly. This is because the machinery, planting, and upkeep of trap crops can be set for one species instead of having to be changed to meet the needs of different species. As a trap crop is likely to decrease pesticide application to control pest insects, such as weta, one trap crop species is still an ecological result worth pursuing.

The results from choice tests in Chapter 3 suggest that, of all the non-vine treatments, broad bean is the most suitable plant species to trial as a trap crop plant in the Awatere Valley. The amount of broad bean eaten was significantly more than all other non-vine treatments across different bioassays in the Bud and Leaf Trial. Broad bean was also eaten on significantly more occasions than the vine treatment when in the same bioassay for both the Bud and Leaf Trial. However, as non-vine treatments significantly decreased the amount of vine leaf eaten across different bioassays, the results need to be taken with caution. Future testing should include choice tests with many more replicates of the pairwise combinations used in Chapter 3. This may reveal a greater, and possibly significant, difference between the amount of vine eaten across different bioassays. Nevertheless, trials should be conducted where weta herbivory takes place on vineyards. These trials should take into consideration abiotic factors such as the pacific afternoon winds, dry climate, and vineyard irrigation policies. These factors could not be accounted for in the laboratory choice tests and will undoubtedly affect the relationship between the cash crop, the trap crop, and pest herbivory. Additionally trials should be conducted to isolate how far *H. promontorius* travel from their burrow in order to feed on a preferred trap crop plant. The results will help determine the positioning and regularity of trap crops planted in the vineyards.

Objective 3: Transect trial results, and suggestions for future research

Determining factors which influence weta abundance, in principle, would allow vineyard managers to predict outbreaks and potentially manipulate abiotic and biotic conditions on the vineyard to manage *H. promontorius*. This trial concluded that *H. promontorius* prefer to burrow underneath vines, and tend to burrow in soil with less penetration resistance. However, strategies to influence soil resistance underneath the vines, such as a reduction in irrigation, are limited because they may damage the cash crop plants. Therefore, methods to control *H. promontorius* need to be based around providing attractive conditions that are not directly underneath the vines. Trap crops, for example, could lure weta away from the vines, so that weta may choose to burrow in areas closer to the trap crop plants.

To confidently predict conditions which could lead to outbreaks, using computer modelling, more replicates need to be taken on the current distribution variables and other variables need to be tested which have proven to influence the abundance of other gravid insects such as slope, chemical composition of soil and humidity (Mbata 2004).

Objective 4: Weta policy analysis, future research

The conservation of iconic pests is driven by a commitment from both organisations directly affected by the damage and conservation groups. If left to businesses, solutions to pest damage are going to favour a quick strategy at the expense of the animal population's survival. Thus, government departments need to consider policies that prevent iconic species from becoming threatened. Policies such as protection status, scientific advice, and collaborations with education institutes could be the driving force for companies to explore EE control methods for weta, as could discovering that weta provide marketing opportunities. However, for optimal conservation results for an iconic pest such as the weta, vineyard companies need to ensure that conservation is part of their overall businesses culture.

6.2 Final summary

This thesis sought an approach outside of orthodox pest management due to the iconic status of weta in NZ and the growing body of evidence which suggests synthetic pesticide is harmful to human health, groundwater, and beneficial insects. . To meet this challenge, control strategies based on agroecology principles were explored for *H. promontorius* herbivory on vines. Recently trap-cropping has become a popular form of habitat manipulation under integrated pest management and ecological engineering systems. As a result, once favourable conditions to maintain weta health were established in Chapter 2, feeding choice tests were conducted which isolated broad-bean as a potential trap crop to control *H. promontorius* vine herbivory. Broad-bean is an exciting prospect as a trap crop species because it may not only draw weta away from vines but also attracts beneficial insects such as parasitic wasps which feed on other vineyard insect pests . However, as trap crops can be employed with different spatial and temporal constraints, it was important to try and isolate where *H. promontorius* is distributed and correlate the distribution with abiotic variables. This thesis confirmed that *H. promontorius* distribution is not significantly different in the edge compared to the centre of a vine block and prefers burrowing underneath a vine trunk compared to between rows. Therefore, if trap crops were to be planted, they would need to consider attracting weta away from the edge and centre of the vineyard. However, as agroecology policies tend to be more expensive and time consuming, ecological engineering strategies appear to need a commitment not only from a business but other stakeholders as well. In fact, my policy study showed that government input and a strong environmental culture embedded in a business are both important components to control and conserve an iconic pest. As a result, if ecological research suggests a certain control method may be effective at managing a pest, it may not come to fruition if businesses and governments are not supportive of the agroecology strategy.

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